4 Development through Sensorimotor Coordination

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At every moment of our lives, there is something going on, some experience. We see, hear, smell, touch, think.

—Varela, Thompson, and Rosch 1993, 59

Piaget (1952) described a pattern of infant activity that he called a secondary circular reaction. A rattle would be placed in a four-month-old infant's hands. As the infant moved the rattle, it would both come into sight and also make a noise, arousing and agitating the infant and causing more body motions, and thus causing the rattle to move into and out of sight and to make more noise. Infants at this age have very little organized control over hand and eye movement. They cannot yet reach for a rattle and if given one, they do not necessarily shake it. But if the infant accidentally moves it, and sees and hears the consequences, the infant will become captured by the activity—moving and shaking, looking and listening—and incrementally through this repeated action gaining intentional control over the shaking of the rattle. Piaget thought that this pattern of activity—an accidental action that leads to an interesting and arousing outcome and thus more activity and the re-experience of the outcome—to be foundational to development itself. Circular reactions are perception-action loops that create opportunities for learning. In the case of the rattle, the repeated activity teaches how to control one's body, which actions bring held objects into view, and how sights, sounds and actions correspond.

Edelman (1987) also pointed to the coupling of heterogeneous sensorimotor systems in the creation of cognition. Edelman's theory starts by recognizing the multimodal nature of the brain at birth; it is—from the start—a complex system made up of many heterogeneous, overlapping, interacting and densely connected subsystems. Like Piaget, Edelman proposed that development occurs through activity dependent processes.

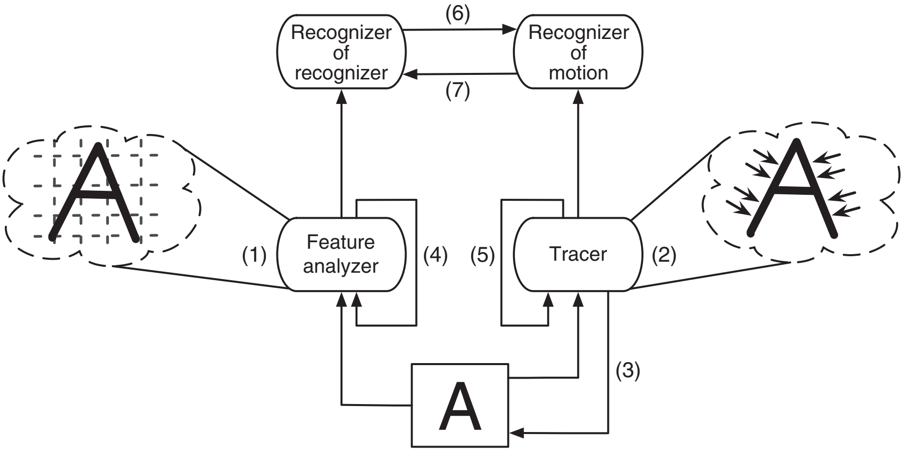

Figure 4.1
Depicts a schematic of Reeke and Edelman's (1984) network model of letter recognition. The letter A at the bottom of the figure depicts the two-dimensional input array. This input is connected to both a feature analysis system and a tracing system. The recurrent connection for the each of these systems represents the system's dependence not only on input but also on its own history. The feature analysis system is composed of feature detectors, which track the local structure of the input array, like an oriented line segment. This system outputs to a more abstract detector that integrates information across the local detectors capturing the global structure of the input array. The tracing system scans the input array and detects the contour of objects. This system, like the feature analysis system, outputs to a higher-level network that captures shared characteristics of related input arrays. The two higher-level networks are connected to each other, enabling the two subsystems (feature analysis and tracing) to work together to classify letters.

Reeke and Edelman (1984) presented one demonstration of this in a computational device that learned to recognize letters merely from interacting with them. Figure 4.1 provides a schematic illustration. This letter-recognition device self-educates through the interaction of two subsystems as they simultaneously process the same physical stimulus. In the feature-analysis subsystem, line detectors are excited by corresponding patterns of stimulation. In the tracing subsystem, information about shape is gained through "eye-movements" as the letter is scanned. The developmental power is in the coupling. At the same time that the feature analyzer is analyzing features, the shape tracer is extracting a global description of shape. The outputs of these two heterogeneous processes, at every step in time, are mapped to each other.

There are seven mappings being accomplished simultaneously in real time. The feature analysis map (1) maps an input letter to a list of features. The tracing map (2) maps the input letter to the actions sequences of scanning. The next map—(3) from the tracing process to the physical world—determines moment by moment the input available to both subsystems. There is also the recurrent activity within each subsystem (maps 4 and 5): at any moment in time, the activity within a subsystem depends not only on the current input but also on its just preceding state. Finally there are what Edelman calls "re-entrant maps" (6 and 7); these map the activities of the two subsystems to each other. Thus, two unique subsystems take qualitatively different glosses on the perceptual information and through their re-entrant connections, by being correlated in real time, by being coupled to the same physical world, they educate each other. Reeke and Edelman's simulation successfully taught itself to recognize all varieties of A, generalizing to novel fonts and handwriting, merely from the activity of looking at As.

The thesis of the present paper is that activity-dependent multimodal experience is a core mechanism creating developmental change. This is certainly a classic idea in perceptual learning (e.g., Held and Hein 1963) but also one receiving increasing attention, in cognition and cognitive neuroscience (Barsalou et al. 2005; Martin and Chao 2001; Pulvermüller 1999; Pulvermuller et al. 2005) and in computational studies of learning (Lungarella et al. 2005; Lungarella and Sporns 2005). Here, we review behavioral evidence from human development, evidence that suggests that transformative change is driven by the sensor-motor coordinations of an active agent in a physical world.

4.1 Actions Create Coordinations

. . . constrained by a history of coupling with an appropriate world.
—Varela, Thompson, and Rosch 1993, 151

The human sensorimotor system is far more complex than the model system shown in figure 4.1. There are many more component subsystems and patterns of connectivity among them. The specific task at hand appears to organize and configure these subsystems differently, softly assembling different coordinations. In this way, different tasks create unique opportunities for change in the system. One method used by developmentalists is to give infants a novel task and then examine how experimentally induced coordination drives change in the specific task as well as how task specific

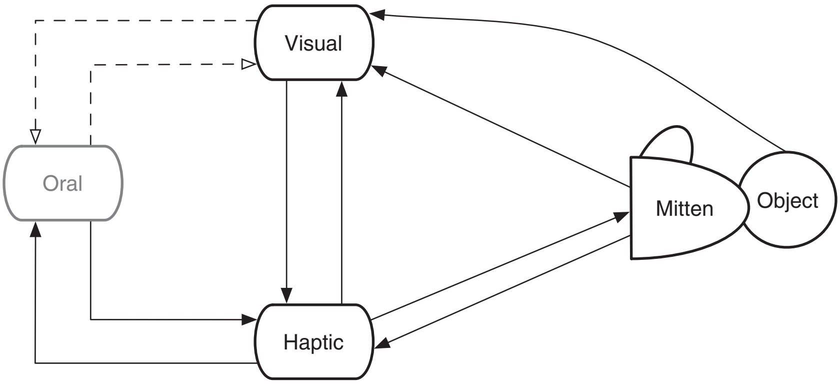

Figure 4.2
Depicts a schematic illustration of the affect of "sticky" mittens on the visual, haptic, and oral systems. The use of sticky mittens during manual exploration reorganizes the coordination of the visual and haptic systems. Although the oral system, grayed in the figure, is not directly involved in this activity, it is connected to the haptic system (infants manually and orally explore objects) and through this connection is potentially influenced by the visual-haptic reorganization.

changes generate cascading consequences in the system as a whole. These kinds of studies, termed "microgenetic studies" in the literature, are particularly powerful methods in the study of developmental process because such studies experimentally create developmental change.

In a recent and remarkably inventive demonstration of this approach, Needham, Barrett, and Peterman (2002) fit two- to five-month-old infants with Velcro®-covered "sticky" mittens. These mittens enabled the infants to grab objects merely by swiping at them, enabling them to precociously coordinate vision and reaching. Infants who were given two weeks of experiences with sticky mittens subsequently showed more sophisticated object exploration even with the mittens off. They looked at objects more and made more visually coordinated swipes at objects than did control infants who had no exploratory experiences with sticky mittens. Needham, Barrett, and Peterman (2002) found that the sticky-mitten task not only facilitated the development of reaching for objects but also visual-oral exploration. That is, infants who had experience with sticky mittens looked at objects more—even in nonreaching tasks—and also mouthed and orally explored objects in more advanced ways. Figure 4.2 provides a schematic illustration of what we take to be the profound significance of these results. Two subsystems—reaching and looking—are coordinated in the sticky-

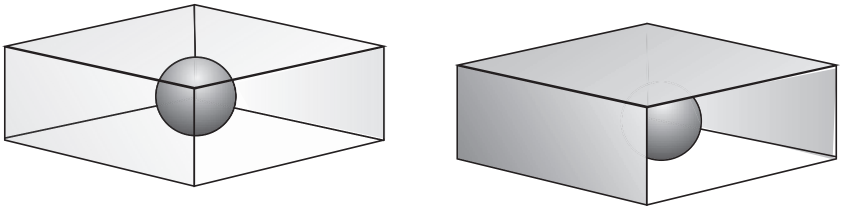

Figure 4.3
Depicts the stimuli used in experiments by Diamond (1990) and Titzer, Thelen, and Smith (2003) on transparency. The picture on the left depicts the transparent box and the picture on the right depicts the opaque box. Both boxes have openings on the right side allowing infants to retrieve contained objects.

mitten task and in so doing educate each other. But these components are also involved in other coordinations, that is, in other tasks that recruit other coalitions of subsystems. Thus, extra experience in the coordination of reaching and looking with sticky mittens ends up not being just about looking and reaching but potentially about other developments, other coordinations, generating cascading developmental consequences in other tasks in which some of the same subsystems are involved.

Another example of how tasks create change that then cascades through out the system concerns transparency. Transparent surfaces violate the usual hand-eye correlations in the world in that one can see the object but a direct line-of-sight reach is blocked. Babies (like birds) have difficulty with this violation of expectation. In one study, Diamond (1990) presented nine-month-old infants with toys hidden under boxes. The boxes were either opaque, hiding the toy, or transparent, enabling the infants to see the toy under the box. As illustrated in figure 4.3, the boxes were open on the side, so that infants, by reaching to that side, could retrieve the object. Diamond found that infants were able to reach around to the side opening given an opaque container but not a transparent one. Instead, the infants attempted to reach for the toy directly banging their hands against the surface seeming generally flummoxed as to how to proceed.

In a microgenetic study, Titzer, Thelen, and Smith (2003; Titzer 1997) gave eight-month-old infants a set of either opaque or transparent containers to play with at home. Parents were given no instructions other than to put these containers in the toy box, making them available to the infants during play. When the infants were nine months old, they were tested in Diamond's task. The babies who had played at home with opaque containers failed to retrieve objects from transparent containers, just as in the original Diamond study. However, infants who had played at home with the transparent containers sought out and rapidly found the openings and retrieved the object from the transparent boxes. Infants' at-home explorations of the transparent containers did not include the specific task of sideways retrieval of objects, although it seems likely that in their spontaneous play objects were both put into and retrieved from the openings in these containers. Titzer, Thelen, and Smith (2003) proposed that in their play—through the coordination of seeing and touching and putting objects in and out—infants learned to recognize the subtle visual cues that distinguish solid transparent surfaces from openings and had learned that surfaces with the visual properties of transparency are solid. The haptic cues from touching the transparent surfaces educated vision, and vision educated reaching and touching, enabling infants to find the openings in transparent containers.

These coordinations of touch and sight also had broader cascading consequences, as shown in a transfer test using a "visual cliff" (Gibson and Walk 1960). The "visual cliff" is a transparent but solid surface placed over a visual "drop off." Typically, eight- and nine-month-olds avoid the "visual cliff," not moving onto the transparent surface given the visual information of a vertical drop. However, babies who had experience playing with transparent containers happily crawled onto the transparent surface over the visual drop off, showing no apprehension whatsoever. The infants who had extensive play with small transparent containers were apparently both sensitive to the subtle visual cues that specify the solidity of a transparent surface and were confident of its support. Again, two subsystems—seeing and touching—are coordinated when playing with transparent containers, each system educating the other in the discovery of relevant regularities to that coupling. The changes in these component subsystems—the regularities found in one task such as play with small transparent containers—may also be transported to other tasks and other coalitions of subsystems, including those involved in evaluating surfaces for locomotion. In this way, through the coordination of multimodal subsystems in specific tasks, the system as whole—its capabilities and its potential for new learning—also change.

4.2 Actions Create Tasks

The state of activity of sensors is brought about most typically by the organism's motions. To an important extent, behavior is the regulation of perception.

—Varela 1997, 82

If tasks create coordinations, and coordinations drive developmental change, it becomes more important to understand tasks—their definition and creation. Prior to shaking the rattle, or catching a toy with the sticky mittens, infants can have no specific goal to shake or to snatch. There is no such task. Infants discover the task through their own spontaneous actions. The process of goal and task creation is profoundly important to understanding both development and the openness of human potential. Accordingly, we first review two more examples of "task creation" and then consider the deeper theoretical importance of these examples.

The first example is "infant conjugate reinforcement" (Rovee-Collier and Hayne 1987). Infants (as young as three months) are placed on their backs and their ankles are attached by a ribbon to a mobile which is suspended overhead. Each kick produces interesting sights and sounds, providing many time-locked patterns of correlations. Infants themselves discover these relations through their own movement patterns. The faster and harder they kick, the more vigorously the mobile jiggles. This is a highly engaging task for infants; they smile and laugh, and become angry when the contingency is removed. This experimental procedure, like the world, provides complex, diverse, and never exactly repeating events—yet all are perfectly time-locked with infants' own actions. It is spontaneous non-task-related movement that starts the process off by creating the opportunity for the coordination of the infant's action with the mobile's movement. It is this coordination that ultimately defines the task and thus becomes the goal.

The second example is the development of reaching, Thelen et al.'s (1993) week-by-week study of four infants transition from not-reaching to reaching for visually presented objects. Early in development, the presentation of an enticing toy aroused the infants and elicited all sorts of nonproductive actions. These actions were literally all over the place with no clear coherence in form or direction. But by acting, each baby sooner or later made contact with the toy—banging into or brushing against it or swiping it. These moments of contact selected some movements, carving out patterns that are then repeated with increasing frequency. Over weeks, the cycle repeated—arousal, action, and occasional contact. Over cycles, reaches became increasingly stable, more efficient and more effective.

However, the task of reaching is discovered by individual action, and thus, it is specific to the individual. All infants followed the general pattern, but each also had unique subtasks to solve. Some babies at first could hardly lift their arms, but sat placidly watching the world. Other babies were more high-strung and active, flailing and flapping and always moving.

These different babies had to solve very different problems in order to reach out and grasp an object. The flailer needed to become less active and to lower his hands bringing them into midline creating balance. The placid baby needed to be more active, to raise her hands, to lift them up from their usual positions on her side. What is remarkable in the developmental patterns of the children is that each found a solution by following individual action-defined developmental pathways that eventually converged to highly similar movements. Because action defines the task and because action—through the coordination of heterogeneous sensory systems—finds the solution, development is very much an individual and context-dependent matter.

If individual actions create tasks that in turn couple component systems that cause change in the system, what then is universal about the developmental process? Theorists sometimes envision development as movement through a landscape. The classic illustration of this is Waddington's (1957) epigenetic landscape, a three-dimensional surface where the branching and deepening valleys depict the increasing differentiation of structures and processes. Waddington saw the surface of the landscape as reflecting a web of changing probabilities arising from the competitive dynamics of underlying complex processes. These processes included not only multiple-gene products, but cell-to-cell interactions and the mutual influences of the environment and the organism's behavior within the environment. The main idea of the landscape was that as development proceeded, these influences worked together to constrain the possible states of the organism.

Muchisky et al. (1996) envisioned a more dynamic landscape—one in which experiences opened new possibilities, taking development in new directions, not just channeling development into preset outcomes. This more dynamic landscape is illustrated in figure 4.4. The landscape has three dimensions. The first dimension is time. The landscape progresses irreversibly from past to present. The second dimension—the surface—is a measure of the state of the developing system. Each of the lines forming the landscape represent the possible states of the system at a particular point in developmental time. The shape of the lines depicts the dynamics of the moment determined both by the history of the system up to that point in developmental time and the particulars of the moment (e.g., the state of the child as well as the social and physical context). The third dimension of the landscape represents the stability of the system at that point in time and in that context. In this view—the landscape and development itself—is self-organizing. Moment to moment, the state of the system and the task

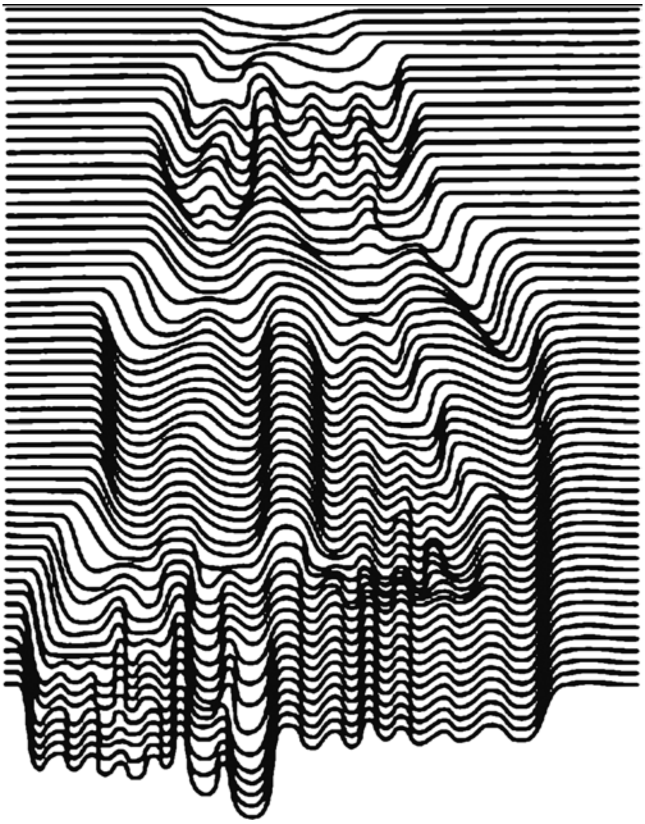

Figure 4.4
The dynamic epigenetic landscape proposed by Muchisky et al. (1996). In this landscape, behavioral development is depicted as a series of evolving and dissolving attractors.

at hand, creates change and, moment to moment, the developmental trajectory. Because of this—because the mechanism of change is the individual's momentary task—development is open to multiple outcomes and multiple paths to the same ends. Each new coordination enables new possible assemblies of subsystems, which generate new actions, which create new tasks (opportunities for reorganization), which create new organizations. The very absence of predefined tasks and the individualistic and opportunistic nature of the tasks that cause change in the system may be the ultimate source of the adaptability and flexibility of human intelligence. Outcomes and developmental process are of course also constrained by the physics of the world and by the intrinsic dynamics of the cognitive system itself. But as a self-organizing complex system that discovers its own developmental tasks through its own action, it is dynamically open and opportunistic.

4.3 Actions Create Developmental Order

> The cognitive self is its own implementation: its history and its action are of one piece.
>
> —Varela 1997, 83

Comparative studies of other species tell us that evolution strongly selects for different patterns of motor development. For example, where species such as horses, cats, and dogs are motorically mature at birth, human infants are motorically altricial. They have very little motor control and indeed must work over the first several weeks of life to merely lift their head. Slowly, they develop enough strength and balance to roll over, to reach, to push into a sitting position (and hold it without falling over), to crawl, and to stand. Each of these achievements is slowly won, through specific interactions with the world, and is indeed individually variable (Thelen 1995; Adolph and Berger 2006). Each of these motor achievements also dramatically changes the tasks that the infant can discover, the coordinations of subsystems, and the developmental landscape as a whole. Once infants can reach for things (at three to six months of age), they can provide themselves with new multimodal experiences involving vision, haptic exploration, proprioceptive input from self-movement, and audition as they contact objects that squeak, rattle or squeal.

Ruff's (1982, 1986, 1989) landmark work on infants' manual exploration of objects presents one example of how the information in the learning environment becomes richer with motor development and experience. Ruff distinguishes several kinds of manual interactions with objects that seem to be used to acquire information (called "examining")—looking, fingering, and rotating (Ruff 1989). By seven months, and more strongly by twelve months, infants give priority to examining over mouthing and banging when faced with a novel object (Ruff 1986). Further, infants' patterns of interactions change within a session as they become more familiar with the object. Their explorations become more object-specific, such that, for example, at seven months, after an initial period of examination, infants begin to bang hard objects more than soft ones (Lockman and McHale 1989; Palmer 1989; Bourgeois et al. 2005), to finger textured objects more than smooth ones, to finger objects more in response to changes in shape and texture than to a change in weight, but to rotate an object and transfer it from hand to hand in response to weight (Bushnell 1982; Bushnell, Shaw, and Strauss 1985; Ruff 1984). These purposeful explorations seem likely to both be informed by and to inform developing visual representation.

After weeks and months of living in this new multimodal venue of sitting, looking, listening, reaching, and manipulating objects, infants' experiences—and the correlations available to them—again change radically, as infants begin to crawl and then to stand up and walk. Self-locomotion changes the nature of the visual and auditory input even more dramatically, and the evidence suggests that it also profoundly changes infants' cognitive development (Campos et al. 2000). One example concerns the A-not-B error. In this task, first used by Piaget (1954), the experimenter hides a tantalizing toy in location A. After a delay, the infant is allowed to search for the toy. On these trials, infants find the toy. After multiple hidings at A, there is the critical switch trial: the experimenter hides the object at a new location B. Infants of eight to twelve months of age reach not to where they saw the object disappear, but back to A, where they had found the object previously. This "A-not-B" error is especially compelling because it is tightly linked to a highly circumscribed developmental period; infants older than twelve months search correctly on the critical B trials.

The shift appears to be tightly tied to self-locomotion. Specifically, individual infants stop making the error when they begin to self-locomote (Horobin and Acredolo 1986). Further, when Kermoian and Campos (1988) experimentally induced early experiences in self-locomotion (by putting infants in walkers), the infants succeeded in the A-not-B task earlier, another example of cascading consequences of activity-generated developmental change. Why should experience in moving oneself about the world help one remember and discriminate the locations of objects in a hide-and-seek reaching task? Because moving oneself about—over things, by things, into things, around things—generates new experiences, new patterns of spatiotemporal relations, and it is the history of these experiences that is etched in the multimodal coordination that alters the infant's representation of objects, space, and self. In order to produce the locomotor movement, a walker must generate a synchronized ensemble of muscle contractions alternating the legs, and shifting the body's weight from one leg to the other as the feet alternate contact with the ground. Continual monitoring by the motor system of the visual system, the vestibular apparatus, and the soles of the feet enables the walker to maintain balance and make corrections for changing biomechanical demands as well as for unexpected perturbations in path, such as obstacles, uneven surfaces, and changes in direction (Thelen, Ulrich, and Wolff 1991). This complex coordination not only enables walking but alters how the infant updates spatial representations with movement (see Luo 2005 for a simulation-based study).

An action in some context creates a task that coordinates multiple sensorimotor systems, and through this coordination, the component systems and their couplings to each other are changed. The next action may form a new consortium of systems, systems that will have been shaped by their participation in previous tasks. Because action creates tasks and transformative change in the components systems, action is a strong organizer of the developmental trajectory itself. Thus, motor development has a strong effect on the ordering of development as a whole.

4.4 Actions Create Higher-Order Concepts

> In brief, the term cognitive has two constitutive dimensions: first its coupling dimension, that is, a link with its environment allowing for its continuity as individual entity; second its interpretative dimension, that is, the surplus of significance a physical interaction acquires due to the perspective provided by the global action of the organism.
>
> —Varela 1997, 81

There is a growing movement in cognitive science—much of it represented in this volume—that suggests that the body creates higher-order concepts through perception and action (see also Varela, Thompson, and Rosch 1993; Glenberg and Kaschak 2003; Clark 2004; Zwaan 2004; Gallese and Lakoff 2005; Núñez and Lakoff 2005; Yeh and Barsalou 2006). We present here one intriguing example of how sensorimotor coordinations and processes much like Piaget's circular reactions may be the developmental engine behind abstract ideas. The phenomenon concerns children's discovery of spatial classification. This kind of classification task—one in which subjects put similar things close in space and apart from dissimilar things—is ubiquitous in psychology. In doing so, subjects use space metaphorically, with nearness in space standing in for similarity. Formal theories of similarity also use space (distance) as the core metaphor defining similarity, for example, Euclidean distance in some feature space (Shepard

1987; Nosofosky 1992). In everyday life, people also put like things in spatial proximity—socks in one drawer, shirts in another, cups on the top shelf, and plates on the bottom. This habit—which allows one to locate and choose among desired objects with ease—demonstrates the functional utility of real space with respect to like things in the real world and may be the root source of the metaphor.

Between their first and third birthdays, children also begin to use space to represent similarity. Indeed, during this period they become almost compulsive spatial sorters. Confronted with an array of four identical cars and four identical dolls, for example, they physically group them—moving all the cars spatially close to each other and spatially apart from the groups of dolls even though there is no explicit task to do so. They are so reliable at doing this that many developmental psychologists use the task as a way to measure young children's knowledge of similarity (Starkey 1981; Nelson 1973; Mandler, Bauer, and McDonough 1991; Mandler, Fivush, and Reznick 1987; Rakison and Butterworth 1998). But, where does this behavior come from? Where does the very idea of spatial classification originate?

The developmental course suggests gradual, action-driven discovery. When nine- to ten-month-old infants are given sets of objects containing like kinds, they do not group them. However, they do pick up objects, one in each hand, and bang them together (Forman 1982). By twelve months of age, these manipulations become more systematic and children manipulate like kinds in a like manner (Sugarman 1983). For example, given four cars and four dolls, the child may systematically push each car. Around eighteen months of age, children not only manipulate objects from one category in sequence, but they also systematically manipulate in different ways objects from two different categories, for example, first pushing each car, but patting each doll. This pattern of behavior—called "sequential touching" in the literature—is compelling to adult observers and seems to be, on the part of the child, a comment on the likeness of the individual instances. From these behaviors spatial classification emerges progressively. At first, spatial groupings seem accidental to acting on like things in like ways (Gershkoff-Stowe and Namy 1995). Around twenty-four months, the sorting seems more purposeful, with all of one kind gathered to form one group and the other kind left unorganized. Ultimately, purposeful, exhaustive, and complete classification of two kinds into spatial groups emerges around thirty-six months.

Four behavioral tendencies in infancy may be enough to start the developmental progression. The first is that infants reach to objects in which they are interested. The second is that infants have a tendency to repeat just performed motor acts, and in particular to repeat reaches to nearby locations (e.g., Smith et al. 1999). Third, perceptually similar objects may be similarly enticing to infants. Fourth, infants may notice the outcomes of their own actions.

A behavioral study with twelve-, fifteen-, and eighteen-month-olds presents support for these ideas (Sheya 2005; Sheya and Smith 2010). In this task, children were presented with arrays of eight toys: five of one kind and three of another. Unlike usual studies of sequential touching or of spatial classification, the objects were fixed to a location by a spring. Fixing the locations and varying the placement of objects in those locations allowed the effect of proximity in space and similarity both to be examined. Because touches to the objects caused them to wiggle and move, the children found the task engaging, making many repeated reaches to the array.

The behavior of the children at the three age levels differed considerably, with the developmental progression being away from perseverative reaches to the same (and nearby locations) toward reaches to the same kind of thing across larger distances. This is shown in figure 4.5. Each panel shows the probability that an infant reached to a location, given that the infant first reached to the center object (marked by a large white dot in the figure 4.5a); the colors—from black to white—indicate an increasing probability that the infant next reaches to that location. The top three panels in figure 4.5b are the twelve-month-olds, the middle panels are the fifteen-month-olds, and the bottom panels are the eighteen-month-olds. The three panels for each age show reaches to three different configurations of the object array in which the locations of the members of the set of five like kinds (indicated by dark gray dots in figure 4.5a) and the members of the set of three like kinds (indicated by the white and light-gray dots in figure 4.5a) are switched. The youngest children most often reached back to the very same object and location but sometimes reached to nearby locations. The similarity of the objects mattered very little to their pattern of activity. The fifteen-month-old children were influenced somewhat by similarity; they also often reached to the same location but were more likely to reach to nearby similar objects than nearby different objects. The oldest children (bottom three panels) also often reached back to the very same object at the same location, but they were much more likely than the younger children to reach to the same kind of thing even at distant locations. In brief, sequential touching is first driven by similarity in location and progressively by similarity of the objects at those locations. One can think of these developmental

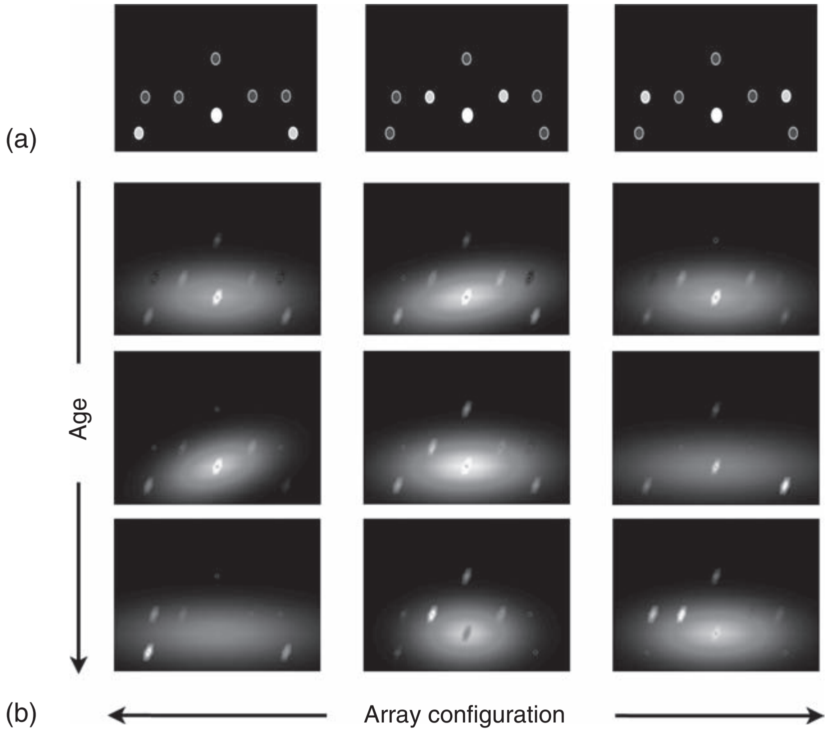

Figure 4.5
(a) The three panels depict the array configurations used in Sheya 2005 and serve as the model for each column of the figure. The large center white dot in each panel represents the location just reached to by the infants. The light-gray dots are locations that contain an object identical to the object in the center location (white dot). The dark-gray locations contain identical objects of a different kind. (b) Each row of panels corresponds to an age group (top panels are twelve-month-olds, middle panels fifteen-month-olds, bottom panels eighteen-month-olds) and each column corresponds to an object configuration. The brightness of a location indicates the probability that infants reached to that location next (lighter corresponding to higher probability and darker to lower probability). The brightness of the distribution around the center location indicates the probability that infants reached to a location that far from the center location next. A brighter, tighter oval would indicate that after reaching to the center, infants next reached to locations nearby. A dimmer, broader oval indicates that infants were more likely to next reach to locations further away from the center.

differences in terms of the changing dynamics of a saliency map: early in development salience spreads uniformly about an activated *location* and later in development salience spreads by similarity to objects with the same *properties*.

What might drive a change in the intrinsic dynamics of such a saliency map? We think it likely that it is action itself. In the child's normal course of action, objects are not fixed to their location. An object once grasped and then let go is unlikely to be dropped at the exact same place in which it was first picked up. Thus a perseverative reach—though in normal interaction with objects this will not occur—to very same location would typically lead to an empty hand. Thus, interaction with untethered objects in the everyday world practices object-based—not location-based—reaching. Nonetheless, the main point is this: a system whose activity is biased to both reach to similar locations and to reach to similar objects will, as a consequence of reaching and moving those things, end up with similar things near each other.

Perseverative reaching to similar things and dropping them near each other is not enough by itself to create the goal of spatial classification (although it could create the result). To create the goal, the child has to notice and like the outcome (as in the cases of shaking a rattle or jiggling a mobile with kicks). Namy, Smith, and Gershkoff-Stowe (1997) reported a result that suggests that young children do notice (and appreciate) the consequences of their own unplanned spatial groupings. The children's "training" was a fun task of putting objects into a shape sorter. As illustrated in figure 4.6, the shape sorter was a transparent container structured so that children could see the objects once they had been dropped inside. Children were given two different kinds of objects (e.g., blocks and dolls) that might be put into the container. In the experimental training condition, the opening on the top of the shape container allowed only one type of object to fit inside the hole. The children were eighteen-month-olds with perseverative tendencies to repeat the same action, and so they (quite happily) attempted to put all the objects into the container—the kinds that fit and the kinds that did not. But, of course, only one kind fit, leading to an outcome of one kind visibly near each other in the transparent container and the other kind spatially separate form these. Namy, Smith, and Gershkoff-Stowe (1997) found that children who participated in this shape-sorter task spontaneously spatially grouped even novel sets of objects in a transfer task. Children who participated in a control group in which all objects (of both kinds)

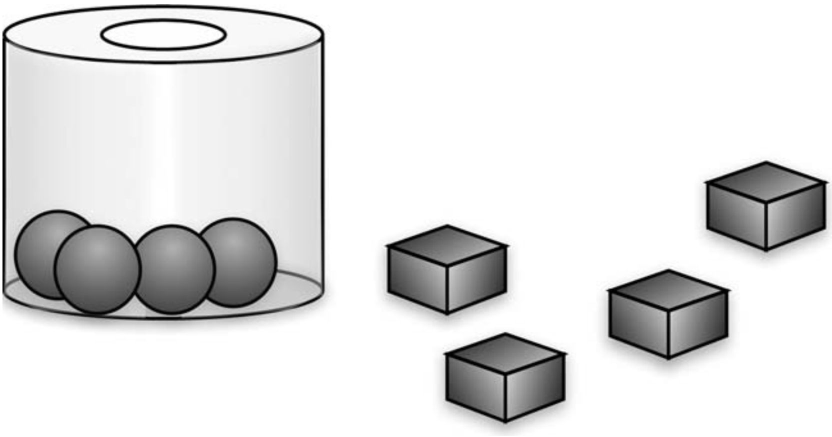

Figure 4.6
Depicts the transparent sorter used in Namy, Smith, and Gershkoff-Stowe 1997. The sorter enabled young children to spatial segregate objects of different kinds.

fit into the shape sorter did not. It seems likely that children in the training condition noticed the product of their own actions—like objects near each other and apart from different objects—and this outcome then defined a new task.

Because action modifies the world in perceivable ways, action can create higher-order regularities—abstractions—like the metaphor between space and similarity. In 1998, Alan Kay (the inventor of programming languages and interfaces that were foundational to the Apple Macintosh) gave a visionary and now-famous lecture entitled "Doing with images makes symbols." The premise was that action and the visually perceived consequences of one's own actions create higher-order abstractions. Karmiloff-Smith (1992) similarly suggested a perception/action/re-perception loop as the foundation of representation itself. In this way, action by creating tasks that coordinate subsystems and leading to perceivable outcomes may be the engine that drives the development of cognition.

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