CHAPTER 4 Dynamic Systems, Sensorimotor Processes, and the Origins of Stability and Flexibility

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Human intelligence reveals both remarkable stability and nimble flexibility. Stability emerges from the incorporation of the past into the present. Flexibility, in turn, requires an abandonment of (or selection among) past ways, a shifting of responses to meet new circumstances. All of cognitive science, one way or another, is concerned with processes of stability and/or flexibility (see Samuelson & Smith, 2000). These are also the core issues in this volume, a volume ostensibly about connectionist versus dynamic systems approaches to cognitive development. My charge in writing this chapter was to consider infant perseveration in the A-not-B task from a dynamic systems point of view. And so I shall. But my main point is not an argument for dynamic systems over connectionism, as that seems not to be an argument much worth having (see Samuelson & Smith, 2000). Much more interesting are the phenomena themselves. Furthermore, both connectionist and dynamic systems accounts of the A-not-B error provide insight into the multilayered and nested dynamics that make up human intelligence.

And our intelligence, for the sake of coherence, always leans a bit to the just-previous past and is thus susceptible to perseveration—stable patterns or stability. This is a main point of this chapter. A second point is that human intelligence is also always open to sensory input and is thus always being perturbed. These perturbations can yield either variability or new stable patterns. It is the latter result that yields flexibility. The dynamic systems approach to the A-not-B error has provided new insights into the phenomenon itself, into the larger issues of stability and flexibility, and into the multilayered dynamics of the sensorimotor processes that underlie all of these.

In this chapter, I first present an overview of a dynamic systems account of the A-not-B error in infants. Second, I present evidence on how the processes that give rise to perseveration in infants are also processes that, in a quite positive way, create coherence and stability. Third, I present evidence on how flexibility emerges in this same system. I then consider the role of sensorimotor processes and implications of this work.

Activation of a Motor Plan: The A-not-B Error

Jean Piaget (1963) viewed cognitive development as the progressive differentiation of internal representations from sensorimotor processes. Advanced forms of cognition were those that were separate from the here and now of perceiving and acting. The A-not-B task, along with the object concept this paradigm sought to measure, played a central role in then-current theorizing. The object concept was defined as the belief that objects persist in space and time independent of one’s own perceptual and motor contact with them. The finding that infants search for a hidden object where they have just previously acted rather than where they have last seen the object disappear was taken as indicative of representations that are sensorimotor in nature.

The A-not-B task begins with the experimenter hiding an enticing toy under a lid at location A. After a delay (typically 3–5 s), an infant is allowed to reach, and most infants reach to location A and retrieve the toy. This A-trial is repeated several times. Then, there is the crucial switch trial: the experimenter hides the object at location B as an infant watches. Where does an infant reach? After a delay, infants 8–10 months of age make the characteristic A-not-B error: that is, an infant reaches back to location A where the object had been found previously. Infants older than 12 months of age usually reach correctly on the crucial B-trials (see Wellman, Cross, & Bartsch, 1986). Piaget suggested that this pattern indicates that older infants, but not younger ones, know that objects can exist independently of their own actions. There has, of course, been much debate about this conclusion, and many relevant experiments tested a variety of alternatives (Acredolo, 1979; Baillargeon, 1993; Bremner, 1978; Diamond, 1998; Munakata, 1998). Indeed, the A-not-B task is now widely understood as one of a class of executive control tasks that require flexibility in the face of a past, stable response (Diamond, 1991; Munakata, 1998; Zelazo et al., 2003).

The dynamic field account (Smith & Thelen, 1993; Smith, Thelen, Titzer, & McLin, 1999; Spencer, Smith, & Thelen, 2001; Thelen, Schöner, Scheier, & Smith, 2001; Thelen & Smith, 1994) focuses on the sensorimotor processes that underlie a reach to a location in space and, in this way, returns to Piaget’s original idea that the error is sensorimotor in its origins and reveals the nature of sensorimotor represenations. The dynamic field account begins with a task analysis of these sensorimotor processes as illustrated in Figure 4.1. In the A-not-B task, infants look at objects at particular locations, and then—repeatedly—reach to those locations. Thus, the infant first watches a series of events: the toy being put into a hiding location (a well) and then covered with a lid. From this, the infant must formulate a motor plan to reach and must maintain
the plan over the delay, and then execute the plan. Motor plans are themselves abstract in the sense that they are not descriptions of particular muscle movements (or even plans about specific movements using a particular body part). Motor plans can be represented with respect to multiple spatial reference frames (with respect to objects in the visual field/world,

Figure 4.1. Task analysis of the A-not-B task: Typical hiding event at location A The box and the two hiding wells (location A and location B) constitute the continually present visual input. The specific or transient input is the hiding of the toy in a well (location A in the event depicted). A delay is imposed between hiding the toy and allowing the infant to reach. During these events, the infant looks at the objects in view, remembers the cued location, and undertakes a planning process leading to the activation of reach parameters, followed by reaching itself.

to eyes, to the head, to effectors such as arms/hands, and to processes that transport them from one place to the other); but ultimately, motor plans must specify the relation between the body, its effectors, and the location of the target (see Cohen & Andersen, 2002). Such a motor plan is necessary in any account of an infant's actual performance of this task and, in and of itself, constitutes a representation of the existence of an object.

Thelen, Schöner, Scheier, and Smith's (2001) formal account of these processes using the dynamic field model is illustrated in schematic form in Figure 4.2. The central figure depicts the activation of a motor plan that codes the direction of a reach. Three dimensions define this motor planning field: the spatial direction of the reach (x axis), the activation strength (y axis), and time (z axis). Importantly, the activation strength must pass some threshold in order for a reach to actually be executed (this chapter returns to this point in the discussion of flexibility). According to the dynamic systems model, activation in this field is driven by three inputs (three panels at left in Fig. 4.2). The first input is the continually present, sensory activation due to the covers/lids atop the two wells; this input drives activation (generally below a reaching threshold) to those two locations. The second input is the hiding event, the specific cue that instigates a rise in activation at one location when the object is hidden. It is this activation from the specific cue that must be maintained over the delay if the infant is to reach correctly after the delay (see Fig. 4.1). The third input is the relatively long-term memory of the previous reaches, which can perturb the evolving activation in the field, pulling it in the direction of previous reaches (i.e., a perservative response). The activation for reaching in the motor planning field (central panel in Fig. 4.2) evolves over time as a function of the sensory events, the dynamics of the activations those events drive, the memories of past reaches, and the
Figure 4.2. Dynamic field model of the A-not-B task: Overview For the A-not-B task used with infants, the motor planning field is depicted and in three dimensions. The x axis indicates the spatial direction of the reach to the right or left; the y axis indicates the activation strength; the z axis is time. As depicted in three panels on the left, activation in the motor planning field is driven by the tonic input of the hiding locations (two wells covered by lids), the transient hiding event, and the memories of prior reaches. The central panel depicts a sustained activation to a hiding event on the left despite recent memories of reaching to the right (that is, a non-perservative response). See text for further explanation of events.

Figure 4.3. Dynamic field model of the A-not-B task: Time-evolution (Panel A) The time-evolution of activation in the motor planning field is depicted for the initial A-trial. The activation rises for A as the object is hidden and, due to self-organizing properties in the field, is sustained during the delay. (Panel B) The time-evolution of activation in the motor planning field is depicted for the subsequent, first B-trial. There is heightened activation at A prior to the hiding event due to memory for prior reaches. As the object is hidden at location B, activation rises at B; but as this transient cueing event ends, activation at B decays and memory of previous motor plans dominate the field. Due to the memory properties of the field, activation increases at A, generating the A-not-B error. (Panels A and B) In these simulations of the model, time is depicted in seconds (100–800 s).
field’s own internal dynamics. The central panel in Figure 4.2 depicts a sustained activation to a hiding event on the left despite recent memories of reaching to the right (i.e., a non-perservative response).

Figure 4.3 shows results from simulations of the model as a dynamic sensorimotor representation. Figure 4.3A illustrates the evolution of activation in the motor planning field on the first A-trial. Before the infant has seen any object hidden, there is low activation in the field at both A and B; this activation is generated from the perceptual input of the two hiding covers/lids. As the experimenter directs attention to location A by hiding the toy, this perceived event produces high transient activation at A. The field evolves and maintains a planned reaching direction to A. The evolution of a sustained activation peak that can drive a reach even after a delay, even when the object is hidden, is a consequence of the self-sustaining properties of the dynamic field. Briefly, the points within the motor planning field provide input to one another such that a highly activated point will exert a strong inhibitory influence over the points around it, allowing an activation to be maintained in the absence of external input.

This dynamic field, the plan to reach, is continuously informed by the sensory input and continuously driven by that input. But the activation in the field is also driven by—and constrained by—memories of previous reaches. Thus, on the second A-trial, there is increased activation at A because of the previous activity there. This combines with the hiding cue to produce a second reach to location A. Over many trials to location A, a strong memory of previous actions builds up; each trial embeds the history of previous trials. Figure 4.3B illustrates the consequence of this on the critical B-trial. The experimenter provides a strong cue to B by hiding the object at location B. But as the activation from that specific cue decays, the lingering memory of the actions at A begins to dominate the field, and indeed, over the course of the delay through the self-organizing properties of the field itself, activation shifts back to the site of habitual activation at A. The model predicts that the A-not-B error is time dependent: there is (all other things being equal) a brief period immediately after the hiding event in which infants should reach correctly (given that the hiding event was a sufficiently strong, specific cue). Past research shows that without a delay, infants typically do reach correctly in the standard version of the A-not-B task (Wellman et al., 1986).

The model makes a number of predictions that have been tested in a variety of experiments (see Thelen et al., 2001). Because reaching is continuously tied to immediate input, visual events at hiding, at the moment of the reach, and indeed even after the reach has begun can drive a different solution and push the reach to A or to B; this has been experimentally demonstrated (e.g., Clearfield, Dineva, Smith, Diedrich, & Thelen, 2008; Diedrich, Highlands, Spahr, Thelen, & Smith, 2001; Smith et al., 1999). Indeed, simulations from the model can be used to design experimental manipulations that cause infants at 8–10 month of age to search correctly on B-trials or that cause children at 2–3 year of age to make the A-not-B error (Schutte, Spencer, & Schönér, 2003; Spencer, Smith, & Thelen, 2001). Such effects can be achieved by changing the delay, heightening the attention-grabbing properties of covers/or hiding event, or by increasing/decreasing the number of prior reaches to A (Diedrich et al., 2001; Smith et al., 1999). All these effects show how the motor plan is dynamically connected to sensory events and motor memories. Because one can make the error appear or disappear in these ways over a broad range of ages (8–30 months), we know that the relevant processes cannot be tightly tied to one developmental period. Instead, changes in A-not-B task performance may be reflective of general processes that govern spatially directed action. The dynamic field model explicitly incorporates this idea by showing how seemingly qualitatively distinct patterns—perseveration, non-perseveration—emerge through small changes in the parameters.

Most critically for the discussion in this chapter, the processes that underlie the behavior—the activations in the dynamic field—are conceptualized as motor plans, plans that take the hand from its current location to the target. Memories for previous reaches—the memories that create the perseverative response—are also motor plans. That is, by this account, the processes that create the error reside close to the sensorimotor surface and are embedded in, not separate from, the processes of perceiving and acting. By this account, and as Piaget originally proposed, the A-not-B error arises from sensorimotor representations.

There is strong experimental support for this view. In particular, manipulations that distort the body’s posture erase the memory for prior reaches and thus erase the cause of perseveration, leading to correct reaches on B-trials (Lew, Hopkins, Owen, & Green, 2007; Smith et al., 1999; Smith, Clearfield, Diedrich, & Thelen, 2008, in preparation). In one experiment, infants were in one posture (e.g., sitting) on A-trials and were then shifted to another posture (e.g., standing) on B-trials. This posture shift between A- and B-trials (but not other kinds of distractions) caused even 8- to 10-month-old infants to search correctly, supporting the proposal that the relevant memory is a motor plan. To be effective, motor plans must be in the coordinates of the body’s position, that is, tied to the current relation of the body to the physical world. Thus, it makes sense
that these memories for prior motor plans are not activated unless the body is in the proper position with respect to the targets in the world.

These results, and the conceptualization of the relevant processes as motor plans, fit well with Piaget's (1963) original conceptualization of A-not-B errors as representations tied to one's sensorimotor interactions with objects. The posture-shift results, in particular, fit with Piaget's idea that, for the young infant, the mental object and its location are inseparable from bodily action.

Such sensorimotor representations were considered by Piaget to be a limitation of an immature cognitive system. But the dynamic field account views these representations as general mechanisms underlying visually guided reaching at all ages. Might this form of sensorimotor representation that is so ill-suited to Piaget's A-not-B task be, in other contexts, a positive aspect of human intelligence? Might the processes that create the stability that leads to perseveration in the A-not-B task also create beneficial coherence in other tasks?

Stability and Coherence: The Baldwin Task

By the dynamic systems account, infants keep track of objects in the A-not-B task by forming a plan for action, a motor plan of how to move the hand to the object's location. Because the motor plan necessarily specifies a target location, that plan represents the object's existence as a location. Activation of one component of this representation can give rise to activation of other components. Thus, in the A-not-B task, activation of the memory of the object and a goal to reach (through the hiding event at B) activates the prior motor plan and yields a reach to A. But this is just one possible consequence of the binding of an object to a location through an action plan. Activation of the action plan (and past location as a goal to reach), should also work to call forth the memory of the nonpresent object.

This section describes a series of recently completed studies that show how the same processes that create the A-not-B error (i.e., an inappropriate stability, given the task) also create coherence in other tasks, enabling the appropriate connection of an immediate sensory event to the correct contents in the just-previous past. The new task concerns how older infants (18–24 months of age) map names to referents when those names and referents are separated in time and occur in a stream of events with multiple objects and multiple shifts in attention among those objects. The experiments use an ingenious task that was created by Baldwin (1993) to study early word learning, but which is, in many ways, a variant of the classic A-not-B task.

The stream of events in Baldwin's task is illustrated in Figure 4.4A. The experimenter
The Baldwin task: Events in three different conditions in each condition, two novel, unnamed objects are repeatedly presented (2 or 4 times) with the respective side of presentation specified by the procedure. A verbal label is then provided for one object without the object in view. Subsequently, the objects are presented in a novel location and on top of each other (so that there are no spatial cues), and the child is asked which one is the referent of the label provided earlier. See text for further clarification.

sits before a child at a table and presents the child with first one unnamed object on one side of midline and then with a second unnamed object on the other side. This is repeated. Out of the sight of the child, the two objects are then put into containers, and the two containers are placed side by side on the table. The experimenter looks into one container and says, “I see a modi in here.” The experimenter does not show the child the object in the container. Later the objects are retrieved from the containers and presented in a new location; the child is asked which one is a modi. Notice that the name and the object were never jointly experienced. Baldwin showed that young children nonetheless connect the object name to the correct object even though that object is not in view when the name is heard.

Figure 4.5 illustrates the A-not-B task and the Baldwin task showing their similar surface structures. In the A-not-B task, children turn to look at and reach to an object at a particular
Parallel steps in the A-not-B task and the Baldwin task

In both the A-not-B task and the Baldwin task, children repeatedly look and reach to locations to interact with objects. (Top panel) In the A-not-B task, an object is presented at location A causing motor planning memory biased to location, and in this way, binding the object to location A. (Bottom panel) In the Baldwin task, two objects are presented at specific locations and—through remembered motor plans and attentional plans—remain bound to the respective locations. Children can then use this binding of objects to locations to link a name to a nonpresent object.

By hypothesis, this binds the object to the action plans of looking and reaching to that location. Subsequently, the goal of reaching for that object activates that plan and the old target location. In the Baldwin task, children turn attention to two different objects at two different locations and again by hypothesis bind these objects to spatially specific action plans of looking and reaching. If this analysis is correct, then, just as the goal to reach for the one object in the A-not-B task may call up the spatially specific action plan, then so could activation of the action plan—a look to a specific location—activate the memory of the specific object associated with that plan. In the Baldwin task, this association would lead the child to remember the correct object at the correct time, the moment the experimenter offered that name, enabling the child to associate the object and name. Could this parallel account of perseveration in the A-not-B task and successful mapping of a name to a nonpresent thing in the Baldwin task possibly be correct? Is success in the Baldwin task due to the same processes that yield failure in the A-not-B task? A series of recently completed experiments support this idea (Smith, Samuelson, & Spencer, 2008, in preparation).

The first experiment in the series sought to show that a common direction of spatial attention was critical to children's successful linking of the name to the object in the Baldwin task. As in the original Baldwin study, the participants were young children, 18–24 months of age. The experiment replicated the original Baldwin method in one condition, and in a second condition sought to disrupt children's word-object mappings by disrupting the link between the object and a single direction of attention and action, making spatial location more variable and less predictive of specific objects. The method in this new condition, shown in Figure 4.4B, is the same as that in Figure 4.4A except that the two objects were each, prior to the naming event, presented once on the right and once on the left. Thus each object was associated with both directions of attention prior to the naming event. If children keep track of objects through their action plans, and if they link a heard name to a remembered object by common direction of action, then this inconsistency in an object's location prior to naming should disrupt the mapping of the name to the thing in the container. This is what occurred. When each object was consistently linked to one direction of attention, Baldwin's original result was replicated, and the children chose the target object 73% of the time. In contrast, when the objects were not consistently linked to one direction of attention, children chose the target object only 46% of the time (which did not differ from a performance level due to chance). Clearly, children are learning in the task about the relation between objects and their locations and using this relation to coherently connect two events—presentation of a name and presentation of a thing—that are experienced at different moments during the task.
One difference between the A-not-B task and the Baldwin task is that the goal in the A-not-B task is to reach to and obtain the toy. Thus, it seems reasonable that the relevant memory in that task—a memory that represents the existence of the object when it is out of view—might be tied to a motor plan. But is this reasonable for the Baldwin task? Is turning attention to a location also correctly conceptualized as a motor plan? As Allport (1990) put it, attention is for action; we attend to locations in preparation for possible action, and actions are performed toward objects within the focus of attention. Thus, direction of attention, like the direction of a reach, may be coded through sensorimotor representations tied to the body and action. Accordingly, in the next experiment, the question was whether it is the body's direction of attention—and not a specific location in space—that enables children to access the correct object when the experimenter provides the name. If our analysis of the direction of attention as a motor plan for orienting the body in space is correct, then one should be able to activate the memory for one object or the other simply by shifting the child's orientation in one direction or the other. For instance, pulling attention generally to the left during the naming event should activate memories for the object seen on the left and then the name should be linked to that object. The method in this new condition (not shown) was similar to that illustrated in Figure 4.4A except that at the moment of naming, there was just an empty table top—no containers, no hidden objects. With the experimenter looking straight into the child's eyes, but with one hand held an arm's length to the side, the experimenter clicked her fingers and said, “modi, modi, modi.” The clicking fingers and the outstretched hand directed children's attention to that side, so that when the child heard the name, the child was looking to that side. Later when children were asked to indicate which object was the modi, their responses indicated that the directional orientation at the moment of naming influenced their mapping of the name to the nonpresent object. Children chose the object spatially linked to the clicking fingers 68% of the time. This suggests that the direction of bodily attention is bound to the object. These results also highlight how the solution to connecting experiences separated in time may be found in the child's sensorimotor engagement in the task.

If the relevant link between objects and locations in the Baldwin task are through motor plans and thus close to the sensory surface, are they also disrupted by shifts in the body's postures? The bodily direction of attention, like a reach, is necessarily egocentric. Just how one shifts one's direction of gaze or turns one's body to bring an object into view depends on the body's current position in relation to that object. Accordingly, the next experiment altered children's posture. One posture setting consisted of the child sitting low and close to the table such that looks right and left (and reaches left and right) required lateral bodily moves. The second posture setting consisted of the child standing on the edge of the table so that the child looked down with a bird's eye view of the locations. The method was the original Baldwin task with containers as in Figure 4.4A. More specifically, in one condition, the child sat (as in the previous experiments) when the objects were first presented (unnamed) and attention and was individually cued to each object at a different location. By the present theoretical analysis, this should associate the two objects with opposing directions of attention. Then during the naming event, the child stood up. If the memory of a previously experienced object is strongly linked to a plan for action, then this posture shift—by necessarily causing a reorganization of that plan—should disrupt the memory. Recall that in the A-not-B task, such disruption caused a lessening of perseveration and, thus, more correct responses. The prediction, here, is that the posture shift before the naming event should disrupt retrieval of the target object, and children should not be as successful in mapping the name to the object. The full experiment included four conditions: sit-sit, with a visual distraction before the naming event; stand-stand, with a visual distraction before the naming event; sit-stand; and stand-sit. In the visual distraction (no posture shift) conditions, children chose the target (spatially-linked) object on 70% of the test trials; in the posture-shift conditions, they did so 50% of the time (thus, no difference from a performance level due to chance). These results strongly suggest that the memory for previously experienced objects is in or indexed through processes tightly tied to the body's current orientation in space. These are memories in spatial coordinates tied to the body's position. Again, these are representations close to the sensorimotor surface.

These sensorimotor representations give rise to children's ability to successfully map a name to a physically nonpresent object. But these representations appear fundamentally the same as those that lead even younger children to reach perseveratively in Piaget's classic A-not-B task. In one case these processes create coherence in the cognitive system, appropriately linking the correct object in the just-previous past to the immediate input (the naming event), enabling the child to keep track of objects as referents in a conversation and stream of events with attention shifting from one location to another. In the other task, the processes create perseveration, an inappropriate sticking to the past when the immediate cues call for a shift to a new response. Cognitive coherence in the Baldwin task is a good form of perseveration—one that yields a positive outcome. If this analysis is correct, can we alter the Baldwin task to create a task-inappropriate sticking to the just-previous past—a maladaptive stability? To this end, we attempted to create an A-not-B effect within the Baldwin task.
The reasoning behind this version of the experimental task is this: If attentional direction activates memories associated with motor plans that orient the body, then these activated memories should compete with an ongoing sensory event if that sensory input originates from the same place. This is how the experiment tested this prediction: Prior to the naming event, objects were presented four times, one always on one side of the table and the other always on the other side, in order to build up a strong link between a specific direction of bodily attention and each object. During the naming event, the experimenter showed the child one object, pointed to it and named it, but did so with the object (and thus the child’s attention) at the side associated with the other object as illustrated in Figure 4.4C. This should set up a possible competition between the just previously experienced object at this location and the present one that is being named—a competition that, like that in the A-not-B task, might not be resolved in favor of the new cue. The results support this. Children selected the actual object they had seen named only 42% of the time, despite the fact that it was in view and pointed to when named. The prior experience of seeing one object in a particular location disrupted linking the name to a physically present object at that same location. This pattern strongly supports the idea that where one looks selects and activates memories from the just-previous past. This not only creates interference in our task but also creates interference in linking an audible word to an unseen object in the standard Baldwin task.

All in all, these results point to the power of sensorimotor intelligence. These results also fit with emerging ideas about so-called cheap solutions (cf. O’Regan & Noë, 2001), about how higher cognitive ends may be realized through sensorimotor processes and the continuous coupling of the mind to the physical world through the body. Young children’s solution to the Baldwin task is a cheap solution in the sense that it does not require any additional processes other than those that must already be in place for perceiving and physically acting on objects in the world.

**Beyond Sensory Fields to Association Fields**

These results discussed above align with Piaget’s original idea that the A-not-B error was the result of sensorimotor representations, although Piaget missed the positive contributions these representations offer as a means of keeping track of nonpresent things. The Baldwin-task experiments also suggest that Piaget was correct about the emergence of representations not so tightly tied to sensorimotor processes. The present analysis views children’s success in the Baldwin task (as well as infants’ perseveration in the A-not-B task) as a form of sensorimotor intelligence—an intelligence bound to the here and now of perceiving and acting. However, not all aspects of children’s performance in the Baldwin task fit this idea. Critically, once children map the name to the object, their knowledge of that mapping does not appear to be spatially fixed. This is seen at testing when the child is provided with the name and asked to choose to which of two objects it refers. In all the tasks, the objects are presented at a new location, and as shown in Figure 4.4, are overlapping and on top of one another.

Thus, the direction of prior attention and action associated with the name and with the object can not be used to determine the intended target. This is important: The processes that children use to learn the name and the processes that are available to them once the name has been learned are different. When children form the link between the object and the name, they appear to use the spatial orientation of their body to retrieve from memory the nonpresent object. But once this mapping is made, they apparently no longer need any spatial correspondence with past experience to direct attention to the object. The course of events in this experiment is thus reminiscent of Piaget’s (1963) grand theory of cognition in which he saw development as a progression from sensorimotor intelligence to representations that were freed from the binds of the here and now in the Baldwin task, children use sensorimotor processes to keep track of things in space and mind, but naming brings a new index to memory that does not involve the body’s disposition to act.

John Spencer, Gregor Schöner, Larissa Samuelson, and I are currently working on an extension of the dynamic field model to explain this. Figure 4.6 provides a schematic of the main ideas. At the top are two sensory fields, one field for objects plus the spatial direction of attention (Object-Space) and one field for sounds plus the spatial direction of attention (Word-Space).

Within this theory, these are sensorimotor fields because they are driven by and continuously coupled to the sensory input and because they specify an action plan directing attention. As in the original dynamic field model of the A-not-B error, these fields also are driven by memories of their own recent activation. What is different in our new model is that these sensory fields are coupled to each other and to a new kind of field, an association field, which has no direct sensory input and is not a plan for action. Instead, the Word-Object association field has inputs only from the Object-Space field and the Word-Space field; this new association field represents the associations between words and objects in a manner that is unconnected to the spatial context of the original experience. It is, in this formulation, the association field that frees the mapping of words and objects to spatially directed action plans.
This general idea is similar to a proposal by Simmons and Barsalou (2003) concerning the origins of higher cognition in multimodal sensory processes and their associations to each other. Figure 4.7 illustrates this general idea. Consistent with well-established ideas in neuroscience, there are modality-specific and feature-specific areas of sensory and motor (and emotional) representations. These feed into a hierarchical system of association areas. At lower levels, association areas exist for specific modalities, capturing activation states within a single modality. At higher levels, cross-modal association areas integrate activations across modalities giving rise to higher order regularities that are more abstract and that transcend modality-specific representations, but that are nonetheless built from them. The role of the association areas, then, is to capture modality-specific states for later representational use. In this way, they create stabilities that do not lie so close to the sensory surface and are not continuously coupled to sensory input and to action. The extension of the dynamic field model and the proposal of a word-object association field fits this general idea of a multimodal outside-in architecture.

The evidence reviewed in this chapter on the role of sensorimotor processes in the A-not-B task and in the Baldwin task suggests the following: (1) The processes that create perseverative reaching and the A-not-B error are a truly sensorimotor form of stability, realized in self-sustaining motor plans linked to objects and locations. (2) This stability creates what would seem to be a deficiency in infant cognition but is probably more profoundly about the sensorimotor bases of coherence and how those processes connect the events in the just-previous past to those in the present. (3) This sensorimotor intelligence is also a stepping-stone to representations distinct from current sensorimotor representations.

**Flexibility: Specific Cues**

Stabilities are essential to human cognition, otherwise our mental life would flit from one thing to another with every change in sensory input. But too much stability—as the A-not-B error shows—can be a problem. Sometimes a change in sensory events requires a change in response. Where in this conceptualization is the origin of flexibility? It is in the sensory event, in
the cue to shift. Figure 4.2, in its schematic presentation of the dynamic field theory, provides an answer: the strength of the specific cue and the subsequent generation of a sustained peak in a new direction point to flexibility. Many factors are relevant as to whether a peak will form in a new direction (Smith et al., 1999; Thelen et al., 2001). But, critically, since there is one final pathway—for example, the movement of the arm in the A-not-B task—all of these factors must be integrated into a single decision. More specifically, within the model, such a decision—to reach at all—depends on the activation surpassing some threshold, and thus releasing interactive processes among neurons in the field to create a single self-sustaining peak. Critically, then, the key question for flexibility is not simply whether the cue to shift is stronger than past memories, but whether it is strong enough to pass a threshold for self-sustaining cooperative interactions in the field.

In the A-not-B task, after a brief delay is imposed, the activation induced by this specific cue is no longer available and the motor planning peak may decay. However, before the reach, at the end of the delay, comes the signal to reach (the pushing of the box forward into the infant's reaching space). Within the model, the end of the delay and the signal that the infant can now reach is modeled by an increased activation to the field as a whole, a generalized excitation in the motor planning field. This boost in the field's total activation is crucial in that it allows an activation peak to pierce threshold and form a self-sustaining, singular peak of activation that is a decision to reach. Whenever the activation in the field reaches a certain threshold, neural interactions—local excitations and global inhibitions—are set in action, which in turn allow for a single localized peak to form. There is no decision to reach unless activation passes a threshold and a single localized peak, specifying the direction, forms and sustains itself. This means that activation level matters. Just where this peak forms—and whether it forms in alignment with the most recent cue—determines whether the infant reaches flexibly or perseveratively.

In a recent paper, Clearfield, Dineva, Smith, Diedrich, and Thelen (2008) examined two factors relevant to the formation of the activation peak in a reaching task with infants; the salience of the specific cue calling for a shift in reaching direction and a
delay between the cue and when the infant is allowed to reach. By dynamic field theory, flexibility and/or perseveration can occur as a function of the integrative response of the field to both the immediate input and the memory from previous reaches. Altering the relative strengths of these inputs to the decision to reach systematically alters the response of the field. Although perseveration is likely for young infants, (e.g., Clearfield et al., 2006; Munakata, 1998; Piaget, 1954; Smith et al., 1999; Thelen et al., 2001), flexibility is also possible. Perseveration and flexibility—even in an infant system with hard to achieve and rapidly decaying memory for specific input—should be systematically related to the strength of the specific cue and the delay period over which its influence on field dynamics must last. Simulations specifically suggested that with no delay, if cue salience is low enough, there should be perseveration (see Clearfield et al., 2008). This is a new prediction, one critical to the idea that total activation in the field and passing the threshold for the formation of a self-sustaining peak are critical. As the cue strength increases, the perseveration rate should drop as the generated activation is enough to pierce the threshold. With a delay, these same differences in cue intensity, will lead to different effects. Specifically, the simulations indicate that with a delay, perseveration rates depend nonlinearly on the cue strength. In particular, perseveration remains high for a wide range of cue strengths and drops fairly suddenly only at very intense, specific cues to shift to B. Thus, the dynamic field theory emphasizes the critical influence of time as well as the singularity of a decision to act.

Clearfield and colleagues tested these predictions in an A-not-B reaching task with infants at 8–10 months of age. Unlike the traditional A-not-B task, there was no hidden object. Instead, two objects were always in view and the experimenter cued the infant to reach to one or the other by holding the object up and waving it. More specifically, infants were presented with pairs of identical reaching targets. Across three between-subjects conditions, these targets varied in their intrinsic attention-getting properties. In all conditions, the targets were placed on a uniform brown presentation box from which they were picked up and cued. In all conditions, the targets, while sitting on the brown presentation, were the same uniform brown color; thus, the task input was the same in all conditions. However, the undersides of the targets—what the infants saw briefly when the experimenter lifted and presented the cue—differed. In the low-salience condition, the underside and thus transient display aspect of the targets were painted the same brown. In the medium-salience condition, the undersides were painted red, yellow, and blue with stripes and polka dots. In the high-salience condition, the undersides presented multicolored flashing lights. Infants were tested in one of two delay conditions (1 s or 3 s).

The stimulus differences are all strong enough to generate correct reaches on the A-trials (no shift). However, the stimulus differences led to dramatic differences in perseveration as shown in Figure 4.8. With no delay, infants perseverated only when the transient cue signaling a need to shift the direction of the reach was relatively weak, but not when the cue was strong. In contrast, with a delay, infants only succeeded in shifting correctly to B when the cue was very strong. These results tell us that infants—in this task—can be flexible or perseverative, both with and without delays; in this way, the infants, in effect, tell us where flexibility comes from. Flexibility originates in—is in the system’s response to—perturbations from sensory events. This push from the sensory event is just the first step. Those sensory events must give rise to a new self-sustaining stability if there is to be a new behavioral decision and not just variability. Thus, just as stability can arise in the nested dynamics of sensorimotor processes, so does flexibility.
Flexible Responding in a Stable System Requires Sustained Activation

The experiments manipulating the salience of the cuing event in the A-not-B task show how flexibility is, in part, a function of the strength of the stimulus cue signaling a shift (and, although not tested, a function of how strongly that new cue activates appropriate memories of prior reaches). The importance of the strength of the specific cue is consistent with other accounts of the A-not-B error, including the PDP account. However, one new idea in the current version of the dynamic field model (see

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**Figure 4.8. Perseveration under varying cue conditions in the A-not-B task**

The bar chart depicts the perseverative responses of infants (8-10 months of age) under three specific cue conditions (low, medium, or high salience) under delay (3 s lag time) or no delay (1 s lag time) in the A-not-B task. The perseveration score is the percentage of infants exhibiting the A-not-B error during the B-trial in a modified A-not-B task, as described in the text.

Sensorimotor Processes

At any moment in time, the complex system that is human cognition is constrained by the just-recenct past, each moment preceding out of the just-previous moment. But at each moment, ongoing sensory input also impinges on and perturbs these internal dynamics. Therein lies the grist for the emergence of stability and flexibility. As noted at the start of this chapter, all accounts of the A-not-B error (and of executive control in general) recognize this tension between the ongoing activity generated by the just-previous past and the current input. Further, because this tension is everywhere evident in neural processes at many different timescales and in different regions of the brain, this tension between stability and flexibility is played out in many different systems. The dynamic field account—with its emphasis on sensorimotor processes—and the experiments it generates provide a number new insights; four insights on sensorimotor processes are discussed here.

A Sensorimotor Object Concept

By the dynamic field account, objects and locations are bound together—and internally represented—via motor plans, which are themselves tightly tied to the current position of the body. These are dynamic representations, a kind of sensorimotor object concept, that provide a means of keeping track of nonpresent things and events over time. The embedding of representations in specific sensorimotor processes suggests that there is no single object concept anywhere. Classic theories of cognition focused on how stabilities were maintained in the context of varying input. These classic theories explained stability by separating cognition from perception and action. The system was conceptualized as linear and unidirectional, from sense to act, with the think part (as in most rule-based and connectionist models) segregated from perception and action, from input and output. The dynamic field model, along with other embodied approaches to cognition (cf. Barsalou, Breazeal, & Smith, 2007; Smith & Breazeal, 2007), views cognition and representation as being embedded in sensorimotor processes.

Perseveration as a Source of Coherence

Sensorimotor representations tied to the body may seem maladaptive in the context of the A-not-B task (a laboratory task with little in common with real-world tasks), but these representations create coherence as the cognitive system moves from one moment to the next in the real-world task of learning object names. Thus the processes that create the A-not-B error are not primarily about a cognitive deficiency (or immaturity), but rather are about one important form of stability that enables the cognitive system to link cognitive contents through the body's disposition in space to ongoing events in the world (see also Ballard, Hayhoe, Pook, & Rao, 1997). The adaptive value of these processes within the human cognitive system is clearly seen in the Baldwin task and in children's ability to map names to nonpresent things. In a sense, current research on the A-not-B error concentrates on flexibility and ignores the value of stability, even though a system that is too variable (in the sense of shifting with every new stimulus) would not be adaptive, just as a system that is too stable is not. The cognitive achievement that underlies the development of perseverative tendencies in infancy was recently demonstrated in a longitudinal study of the A-not-B error (Clearfield et al., 2008). In that study, young infants (6 month of age) began flexibly following the cue on B-trials, then became perseverative as they grew older. Thus, perseveration in the A-not-B task is a developmental achievement requiring the building of memories of past reaches. (A similar point with a predicted curvilinear developmental trend has also been made by Munakata, 1998).

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also Clearfield et al., 2008; Schöner & Dineva, 2007) is that transient active processes from the specific cue are not enough; instead, the key issue is the ability of the system to stabilize an activation peak that can be sustained by the neural interactions within the system without further input. This is the key point of the experiments showing perseveration even with no delay. No previous account has ever predicted that infants may perseverate without delay because read-out (i.e., response generation) always reflects the instantaneous maximum right after stimulation. This allows for a relatively weak cue to have a direct and thus relatively strong impact, always leading to a correct response without a delay. However, a response will not happen even without a delay unless a threshold that leads to sustained internally generated activation is pierced. Previous studies have shown that infants do not perseverate without a delay between the specific cue and the signal to reach (Marcovitch & Zelazo, 1999; for reviews, see Wellman et al., 1986). This is typically interpreted in terms of perseveration arising from the need to represent the target over a delay (Diamond, 1985; Munakata, 1998)—no delay implies no need to maintain a required representation and thus no perseveration arises. According to dynamic field theory, this is not precisely correct. Perseveration arises because of insufficient activation from the specific cue to the new target. This insufficient activation at the time of the signal to reach may arise either from a weak specific cue or from the decay of activation over a long delay. Flexibility requires not only a strong cue but also a system that can generate sufficient activation to recruit the self-sustaining cooperativity among local elements that is a decision to reach.

**Representations Without Direct Links to the Sensorimotor Surface**

Results in the Baldwin task suggest that sensorimotor processes may give rise to representations that are not linked directly to sensory input (as in the association field depicted in Fig. 4.6). These representations—which also provide input to the motor planning fields—create both a new form of stability and a new way to augment specific cues; thus, these internal activations lead to increased flexibility and appropriate shifting with new cues (see Brown, Reynolds, & Braver, 2007, for research on executive control and attention shifting that fits this conceptualization).

**What Develops During Development?**

The key aspects of the developmental pattern of infant perseveration are these: Very young infants do not perseverate but follow the cue (Clearfield et al., 2006). Infants 8–10 months of age typically perseverate in this task, under both relatively brief and long delays (Wellman et al., 1986). Infants 10–12 months of age will also perseverate, but only under increasing delays between the hiding event and the reach (Diamond, 1985). After 12 months of age, infants do not perseverate, even after very long delays (Wellman et al., 1986). But none of these response patterns are fixed. Instead, the behavioral outcome depends on the strength of the memories of past reaches, on the activation level in the field as a whole, on the decay rates, on the internal dynamics and connectivity in the field, and on the posture shifts. All of these are likely to have some developmental course of their own and may contribute to the overall developmental trend.

Current simulations of the model, however, have concentrated on resting levels of the motor planning field, modeling younger infants and older infants with lower and higher resting levels (Dineva, 2005, unpublished; Dineva, Schöner, & Thelen, 2008, in preparation; Thelen et al., 2001). The higher the resting level, the easier it is to enter the cooperative regime. A strong cue can compensate for the resistance (low resting level), enabling activation to pass the cooperativity threshold. Importantly, what the model predicts given an immature system (low resting level) plus a very strong specific cue versus a mature system (high resting level) plus any specific cue is fundamentally the same: activation reaches a threshold and feeds back on itself to suppress competing activation; this yields a sustained peak and, thus, a behavioral decision. For a younger infant, the amount of activation provided by the specific cue is more crucial in getting to a sustained regime than for an older infant; this is due to the low resting activation level in the field in the immature system of the younger infant. That is, in a more developed system, a sustained regime comes more easily.

The developmental question that needs to be answered is why this resting level goes up as the infant develops. This could be due to fundamental changes in the neural system, including, perhaps, the involvement of larger pathway systems, frontal areas of the brain, or association areas that amplify signals via learned associations and acquired cues (including language). These developmental changes may also be due to specific experience, with the curvilinear trajectory in the A-not-B task being driven by experience in goal-directed reaching itself (see Thelen et al., 2001). The apparently central role of the activation level may also help us understand the vulnerability of compromised systems to perseveration. Such perseveration is a hallmark of psychopathology and brain injury, including injury to the prefrontal cortex (e.g., Luria, Pribram, & Homskaya, 1964). The immaturity of the prefrontal cortex has also been implicated in young infants’ failure to reach correctly on A-not-B tasks (e.g., Diamond & Goldman-Rakic, 1989). Often, variants of the A-not-B task are also used as diagnostic tools in the
assessment of neurological disorders (e.g., Diamond, 2001; Gazzaniga, Ivry, & Mangun, 2002). By the present analysis, the core commonality in immaturity and in neurological damage may be decreased activation, making it more difficult for the system to get above the threshold for cooperativity. Further, damage to the system may result not in loss of some specific functionality, but rather in an unspecified decrease in overall activation levels (Kimberg & Farah, 2000; Farah & McClelland, 1991). For instance, a lesion may cut through a long-distance excitation-inhibition loop between different brain regions, thus reducing cooperative interactions within the system as a whole.

### Conclusion: It's the Brain in a Body in a World that Matters

The dynamic field theory’s account of the A-not-B error—with its emphasis on the sensorimotor processes involved in keeping track of and reaching to objects—makes a unique contribution to the understanding of flexibility and stability (and their development) by showing how these outcomes are the products of a complex dynamic system with many components that is continually coupled to the world through the body. This emphasis on processes close to the sensory surface, on the embedding of cognition in a body in a physical world is the most fundamental difference between the dynamic systems approach and a connectionist approach. Figure 4.9 shows a diagram often used by Randy Beer (Beer, 1995; Beer, in press; Chiel & Beer, 1997), a roboticist, who argues (and demonstrates) that complex systems of intelligence can only be understood through an integrated perspective on environment, body, and brain. He notes that the common way neural and cognitive scientists speak of, for example, “the neural control of behavior” reveals our bias of thinking of the body as a mere puppet responding to the demands of the nervous system (Beer, in press).

Internal representation—the nervous system—is crucially important to integration of information and to the range of behaviors in which the system can stably engage and among which the system can flexibly switch. However, the nervous system, the body, and the environment each possess their own complex intrinsic dynamics, and these are in continuous interaction with each other—always. The child’s mapping of names to things in the Baldwin task, for instance, is built on a spatially ordered world (and spatial biases on the part of the social partner). This spatially ordered world is made up of a perception-action system (that must be tied to the body’s current position in physical space), memories, and integrative processes. In turn, these integrative process are at work on multiple timescales and over many different sensory, motor, and internal sources of information. Human cognition is what it is because of this system as a whole. Evolution selects the

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**Figure 4.9. Coupling of the brain to the body and to the world** This diagram illustrates the concept that the brain is coupled to the body and, thus, to the world. The diagram appears simple; the implications for the real world are complex.
behavioral efficacy of the whole package. Thus a complete explanation of stability and flexibility, of development, and of human cognition in general will require an explanation in terms of the complete brain-body-environment system as illustrated in Figure 4.9. The explanation cannot properly be found in any individual component of this coupled system.

References


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