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5 Five Hunches about Perceptual Processes and Dynamic Representations

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5.1 INTRODUCTION

In everyday encounters with the world we interact with a dynamic environment. Whether hunting game in the Serengeti, fleeing tigers in the Himalayas, traversing the streets of New York, driving on a Los Angeles freeway, dancing the tango, feeding an infant, or cooking dinner with a spouse, a human must coordinate his or her movements with the movements of another moving being.

Most events of consequence, and many more mundane events, involve motor action from the perceiver that is related to action by others. This is true even if the current environment contains no active objects besides the perceiver, for the perceiver may well be planning to act on the environment (by walking through it or by manipulating an object within it). Although it is certainly true that we can sit back passively and perceive events with little direct influence on them, this capacity may well be a by-product of a perception/action system that has evolved to guide adaptive motor actions in the world.

This perspective on perception, that perception is really a perception/action system, has been pushed by others (for instance, Gibson and his followers). I take this perspective too, but I take it in a direction different from Gibson's ecological approach, which postulates direct perception of the affordances of the environment (see Gibson 1979). Along with Shepard (1984), my direction is toward the investigation of perceptual representation. In particular, I theorize that perceptual representations are *dynamic* (Freyd 1987) and that static stimuli invoke dynamic mental representations.

But what is a mental representation? One of my ambitions in this chapter is to suggest an understanding of mental representation that follows from the perspective that human perceivers are especially well suited for interacting with a dynamic environment. In this context I will attempt to break down the structure/process distinction that has dominated cognitive psychology. A second idea I will suggest in this chapter relates to a possible temporal isomorphism between the internal and external worlds. A third goal is to sketch a theory of art perception that follows from my claim that static stimuli point the way to dynamic representations. A fourth aim is to share some ideas about the implications my perspective might have for network models of perceptual processes and representations. My fifth ambition for this chapter is to suggest that although perceptual representations are dynamic, shareable representations (that is, representations that can be readily shared between people) may be more static than dynamic.

Before elaborating on these new hunches, I review briefly some of my empirical and theoretical work on picture perception, representational momentum, and the theory of dynamic mental representations. I then turn to the new ideas. These developments are not yet definitive findings; instead, they are offered as new directions for research.

5.2 REVIEW OF EMPIRICAL AND THEORETICAL RESULTS ON DYNAMIC MENTAL REPRESENTATIONS

I began thinking about dynamic mental representations in the context of two perceptual puzzles: (1) How can readers make sense of handwritten letters and words when there is such variety in the stimulus? (2) How can some static pictures and photographs lead to the phenomenal experience of implied movement?

My answer to question 1 invoked the past: Readers may use handwritten material as a static trace of a dynamic process (Freyd 1983a, 1987; see also Watt 1980). If so, our ability to decode handwritten material may partly depend on our knowledge of how the material was created. Freyd (1983a) demonstrated that knowledge of drawing method influences the recognizability of distorted artificial characters. Babcock and Freyd (1988) found that perceivers are sensitive to information in the static trace that specifies the manner in which a character was drawn. Using actual hand-drawn characters, DeKay and Freyd (in press) showed that drawing method influenced the subsequent discriminability of characters. Zimmer's (1982) results suggest that the relative weight of dynamic versus static information in handwriting recognition varies as a function of legibility and communicative demands. Taken together these findings point to the importance of dynamic information in a perceptual domain that is on the surface static.

My answer to question 2 invoked the future. Consider one sort of static picture that can imply motion—snapshots of objects and creatures captured in the middle of an event. I hypothesized that people might perceive implicit motion when presented with such pictures of "frozen" motion (as in fig. 5.1), where perceiving implicit motion could mean the movement an object would undergo were it to be thawed. These two answers—invoking the past and the future—were united by the idea that some, and perhaps all, perceptual representations include a temporal dimension.

My experimental investigation of question 2 began with a test of the hypothesis that frozen-action photographs might involve the representation of dynamic information (Freyd 1983b). Using pairs of before-and-after pictures taken from action scenes, individual stills were presented to subjects tachistoscopically. The subjects were instructed to look at one picture and hold it in

Figure 5.1 A "frozen-action" photograph that conveys the future of the captured event.

memory, and then to view a second picture and decide as rapidly as possible whether the second frame was "the same as" or "different from" the first. They were shown the pairs in either real order or backward order. Subjects took longer to correctly indicate that the second frame was different when the pair was in real-world temporal order. (The mean response times were 847 ms for real-world and 788 ms for backward correct responses; error rates were higher, but not significantly so, for real-world than for backward test orders.)

Development of the theory of dynamic representations has been heavily influenced by results from studies of *representational momentum.* In our first study on this topic, Finke and I (Freyd and Finke 1984) demonstrated that when a rotation of a visual pattern is implied, an observer's memory for the pattern orientation tends to be displaced forward in the direction of the implied rotation. In a similar, subsequent study (Freyd and Finke 1985), subjects were presented with a static figure in a sequence of orientations sampled from a possible path of rotation (see fig. 5.2). Subjects were instructed to remember the third orientation they saw and were presented with a fourth orientation that was either the same as, or different from, the third. Test orientations were varied parametrically around true-same. We found a generally symmetric unimodal distribution of "same" responses centered not on true-same but on a forward rotation from true-same. That is, subjects showed a shift in memory for position. Effects similar to those found for implied rotational motion (e.g., Cooper et al. 1987; Freyd and Finke 1984, 1985; Freyd and Johnson 1987; Kelly and Freyd 1987; Verfaillie and d'Ydewalle 1991) have

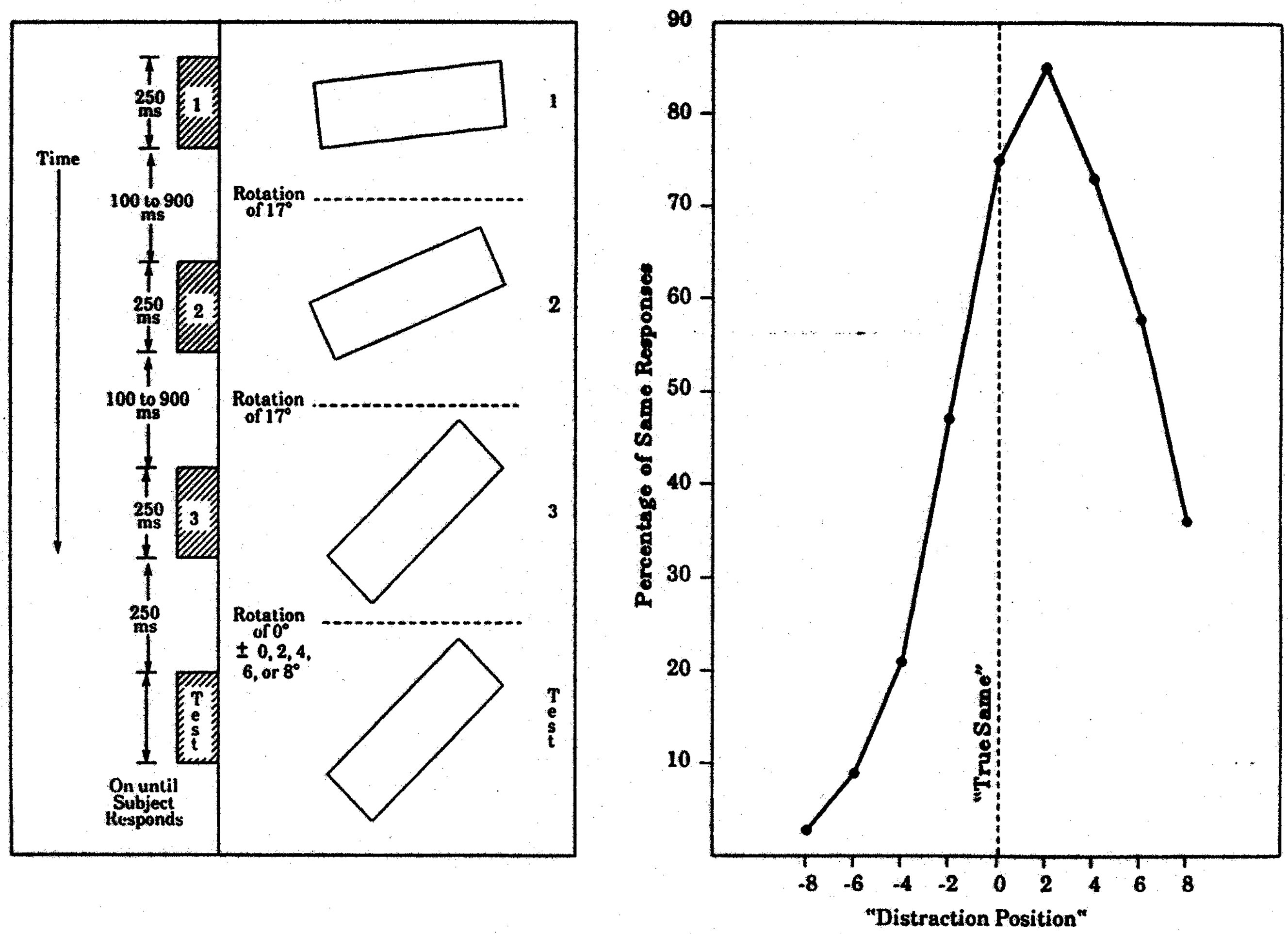

Figure 5.2 Schematic depiction of stimuli and results from a representational momentum experiment (Freyd and Finke 1985).

been discovered for implied translational motion (e.g., Finke and Freyd 1985; Finke, Freyd, and Shyi 1986) and for an implied spiral path (Freyd and Taylor 1990). When the transformation is subjectively continuous (as in animation), the memory displacements may be even bigger (e.g., Faust 1990; Hubbard and Bharucha 1988; Hubbard 1990), although it is difficult to directly evaluate the role of subjective continuity independent from other parameters known to influence the memory shifts such as implied velocity and final stimulus duration (Faust 1990).

Finke and I termed this phenomenon "representational momentum" (Freyd and Finke 1984) because of its similarity to physical momentum, in which a physical object continues along its path of motion through inertia. As with physical momentum, representational momentum is proportional to the implied velocity of motion (e.g., Freyd and Finke 1985; Finke, Freyd, and Shyi 1986), and it also varies with the implied acceleration (and thus implied final velocity) of the pattern (Finke, Freyd, and Shyi 1986). In addition, the amount of memory distortion follows a continuous stopping function for the first 250 ms or so of the retention interval (Freyd and Johnson 1987). Furthermore, these parametric effects have been demonstrated in a nonvisual domain. Using sequences of pitches, Kelly, DeKay, and I (Freyd, Kelly, and DeKay 1990; Kelly and Freyd 1987) replicated the basic phenomenon and showed that it behaved similarly to the visual case with changes in implied velocity, implied acceleration, and retention interval.

Appropriately, representational momentum effects do not obtain under various boundary conditions. When the order of the first two items in the inducing display is reversed, thus disrupting the coherence of the implied transformation, the memory asymmetry disappears (Freyd and Finke 1984; see also Freyd and Johnson 1987; Freyd, Kelly, and DeKay 1990). When the shapes of objects are radically altered from item to item in an implied rotation, momentum effects do not emerge (Kelly and Freyd 1987). And when the inducing display ends with an implied final velocity of zero, the momentum disappears (Finke, Freyd, and Shyi 1986). Similarly, an implied deformation of a rectangle into a perfect square produced no memory asymmetry, suggesting that when the inducing display ends with an item that is prototypical of a category, internal transformations may be halted (Kelly and Freyd 1987).

Although the similarities between physical and representational momentum might be taken as evidence that through natural selection, or the child's interaction with the environment, the human visual system has adaptively acquired rules that mimic physical momentum, I prefer an alternative view (Freyd 1987; see also Finke and Freyd 1989). I understand representational momentum as a necessary characteristic of a representational system with spatiotemporal coherence, just as physical momentum is a property of objects embedded in a spatiotemporal world. I therefore predict representational momentum effects for any dimension affording continuous transformation. From this perspective, representational momentum, rather than being directly adaptive (as in fig. 5.3A), may be a necessary product of the adaptive advan-

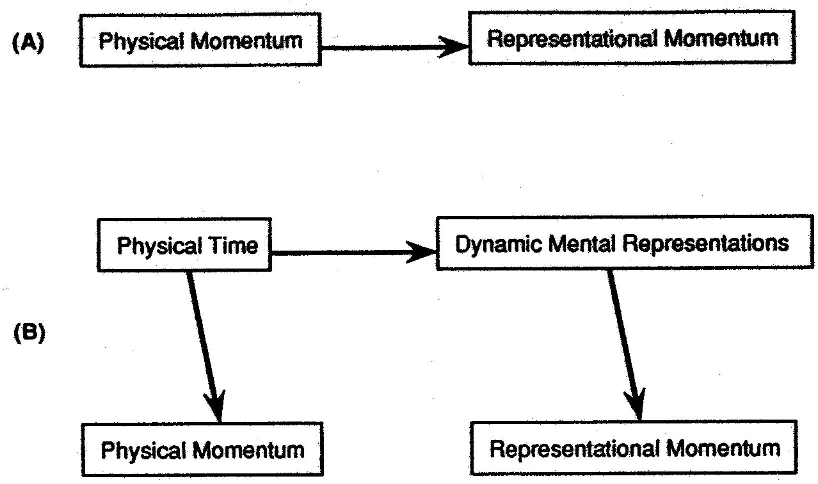

Figure 5.3 Representational momentum, rather than (A) being directly adaptive, may be (B) a necessary product of the adaptive advantage of anticipatory computations and a more general internalization of time (as suggested in Freyd 1987; Freyd, Kelly, and DeKay 1990).

tage of anticipatory computations and a more general internalization of time (as in fig. 5.3B).

Of relevance to this interpretation of representational momentum is evidence that the phenomenon is apparently not particularly cognitively penetrable. The memory task offers subjects an objective correct answer, and obtaining that correct answer requires that the subjects refrain from transforming the stimuli to be remembered; subjects reliably show the effect despite the demand characteristics. Moreover, despite practice and feedback the effect persists (Freyd and Finke 1985). Recently, Hubbard and Bharucha (1988), Ranney (1989), and Finke and Freyd (1989) debated the extent to which representational momentum is penetrable. Finke and Freyd (1989) propose that while the path of extrapolation may be influenced by contextual factors, the forward memory shifts cannot be eradicated by manipulations of conscious beliefs. We thus argue that representational momentum is relatively impenetrable—that is, subjects cannot instantaneously halt the represented motion no matter what they think or attempt. This points to the inextricability of time in representation.

In a line of investigation related to representational momentum studies I have continued to explore the perception of dynamic information in static pictures (Freyd 1983b; Freyd, Pantzer, and Cheng 1988; Freyd and Pantzer 1989). Freyd, Pantzer, and Cheng (1988) hypothesized that implicit physical forces might be one way pictures depicting stable scenes lead to dynamic representations. We presented subjects with drawings of scenes in equilibrium (e.g., a plant hanging from a hook; a box resting on a spring) followed by a depiction of the same scene suddenly in disequilibrium (the plant minus the hook; the spring minus the box) but without any change in position of the to-be-remembered object (the plant, the spring). Subjects made more memory errors in the direction predicted by the disequilibrium than in the opposite

Figure 5.4 An example of a stable still life conveying physical forces in equilibrium: Photograph of a figurehead from the ship *Centennial*, ca. 1875, wood, painted white (courtesy of The Fine Arts Museums of San Francisco, Museum Collection).

direction (thus the plant was misremembered farther down, the spring farther up). This result suggests that lurking behind the phenomenal sense of concreteness one has when viewing some pictures or scenes (as in figure 5.4) may be an underlying representation of physical forces.

Freyd and Pantzer (1990) recently investigated the dynamics of simple static patterns. Some simple static patterns like arrows can produce a compelling sense of directionality (see fig. 5.5). Even equilateral triangles, which lack a conventional interpretation, appear to point in one particular direction at any one time (Attneave 1968; Palmer 1980). We found memory distortions for arrows and triangles in the direction in which they appeared to point, suggesting that the phenomenal sensation of directionality is based on a dynamic mental representation.

These experiments, investigating the perception of dynamic information in static patterns, plus the studies exploring representational momentum, are the empirical basis for my claim that just as time is a dimension in the external world, inseparable from other physical dimensions, so might time be a dimension in the represented world. I have proposed two criteria for dynamic mental representations (these criteria were suggested in Freyd 1987, but they have

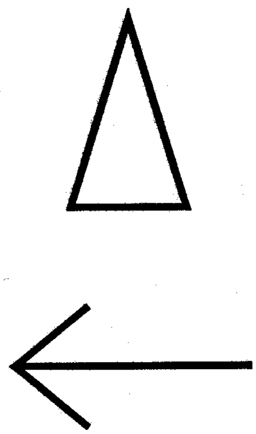

Figure 5.5 Simple static patterns like arrows and triangles may point.

been further developed since then):

1. A dynamic mental representation is one in which the temporal dimension is inextricably embedded in the representation. The representing dimension for time could not be removed from the representation while still preserving a coherent representation. It is mandatory, necessary, and unavoidable.

2. The internal temporal dimension is inherently like external time (at least to a first approximation). For a representation to be dynamic, at least two particular aspects of the temporal dimension in our external world must also be consequences of the inherent structure of the representing dimension.
a. The temporal dimension must be directional; the external time humans confront goes forward.
b. The temporal dimension must be continuous (or as continuous as the mechanics of neural networks permit, which presumably operate at less fine temporal resolution than do potential quantum effects in physical time). Operationally, continuity will mean that between any two points of time, another point of time exists.

Because the continuity criterion is of special relevance to many of the ideas that are discussed in the remainder of this chapter, I will briefly describe the experiment on representational momentum that I think supports this criterion most compellingly. Experiment 1 of Freyd and Johnson (1987) used a standard inducing sequence of three rectangles, each presented ahead of the last by 17 degrees of rotation. As usual, we asked subjects to remember the third position. The test positions were varied parametrically around that third position. Nine retention intervals were used, ranging from 10 to 90 ms in steps of 10 ms. Based on the analogy to an inertial object being stopped, a monotonic relationship was predicted for the relationship between estimated memory shift and retention interval. In fact we found an approximately linear relationship ($r = .98$) between these variables (see fig. 5.6). Other experiments indicate that the memory shift grows for at least the first 200 ms for the standard inducing display using three rectangles.

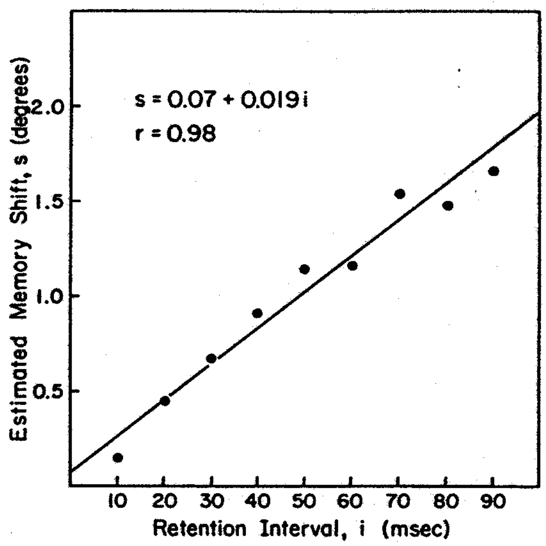

Figure 5.6 Relationship between retention interval (10–90 ms) and memory shift found by Freyd and Johnson (1987).

The strong relationship between memory shift and retention interval may be considered evidence in support of the continuity criterion of dynamic representations. According to this interpretation, our test items constituted probes at 10-ms intervals of the current state of the mental representation. The results indicate that the memory shift increased by minute (fractions of a degree of rotation), but highly predictable, amounts in those small time periods. This finding suggests that Cooper's (1976) probing of mental rotation can be considered in terms of the temporal continuity that it implies (as opposed to the spatial continuity that has been discussed most often). Our results, however, use a much finer gradation of probe times and also are less likely to be influenced by expectations, beliefs, tacit knowledge, or demand characteristics (see Finke and Freyd 1989).

5.3 FIVE HUNCHES

My recent thinking about dynamic representations has suggested to me some new avenues for exploration. For the remainder of this chapter I will turn to five of those new directions.

Hunch 1: Mental representations are a level of analysis.

According to the standard view in cognitive psychology a mental representation is a mental thing—a data structure, as opposed to a mental process (e.g., Anderson 1990, Palmer 1978). Perhaps this definition of representation falls out of the computer metaphor. Whatever its genesis, it has tended to force a notion of representation that is implicitly static. That structure and process models may be formally equivalent is not a new idea (e.g., Anderson 1978);

what is not generally recognized is the extent to which we continue to assume structure/process dualism in theories of mental representation.

One reason to question the structure definition of mental representation is that it seems implausible to suppose that on-line, ongoing computation involves structures that are physically distinct from processes. Indeed, I think the only reason this idea has persisted is that structures have been considered to have some permanence, whereas processes occur in time. Static data structures have some appeal as a description of long-term memory. My struggle with the notion of mental representation, however, is not for the permanent storage of information, but for the active, on-line representation of the external world. The mental representations I want to understand are in the domain of "working" memory, not long-term memory. I do not reject the notion of structure when it refers to the physical architecture of the brain. Instead I reject the idea that active mental representations are separate, static things in the mind.

If mental representations are not static structures, what are they? My proposal is that mental representations are a level of analysis through which we can understand mental mechanisms. But this level of analysis is not trivial; it is crucial, for it allows us to examine the relationship between information in the world and information in the mind. Examining this relationship is the focus of much work in cognitive psychology, whether the phrase "mental representation" gets used or not. In questioning the correspondence between internal and external worlds, investigators have generally focused on two questions: (1) What information is represented?, and (2) How is that information represented (e.g., is continuous information in the world represented discretely in the mind)?

Along with "what" information and "how" we represent it, I propose that we also consider what might be called the "why" questions: why do we represent certain information? What functions of the mind get aided by representing particular sorts of information? My perspective suggests that it is especially important to represent information about the future. Earlier I pointed out that when people interact with the world, they need to be sensitive to real-time change or movement. More than simply to perceive movement, it is highly advantageous to anticipate movement. Even if we are interacting with a static object, for instance when we walk about or start to lift an object, we need to anticipate the effect of our motor movements on the environment. The advantages to anticipating movement suggest that representations of the world might emphasize future time. Yet, classically, time has been a symptom of mental processes, as in chronometric analyses of processes (e.g., Posner 1978; Shepard and Cooper 1982). Thinking of mental representations as a level of analysis of processes allows time to be inextricably part of the structure. With time inside, not outside, the mental representation, the dynamic present and the anticipated future can both be easily represented.

This monist reconceptualization of mental representation, based on a central role for time in the mind, has potential application in a number of areas of cognitive psychology. At a general level, it could facilitate a new sort of interaction between investigators focusing on so-called mental "processes" and those focusing on so-called mental "structures." For instance, we might be able to reconsider theories of attention allocation in terms of the dynamics of mental representation and integrate what is known about aspects of object recognition.

Similarly, seeing mental representations as a level of analysis through which we can understand mental mechanisms may cast new light on a classic debate. Is perception direct and unmediated (e.g., Gibson 1979) or does it instead depend on inferences or mental representations (e.g., Helmholtz [1894] 1971; Shepard 1984)? Whereas we may well still want to debate the extent to which inference is used in perception, a perceiving organism with information about the world has a representation since "representation" refers to the correspondence between information in the world and information in the mind. I would pose the "unconscious inference" question in terms of the knowledge embedded in the representational structure that constrains and shapes the incoming information such that "inferences" are automatically computed given the match between the information coming in and the built-in knowledge. For instance, Shiffrar and Freyd (1990) demonstrated that interpolated paths of apparent motion for views of the human body follow anatomical constraints. I interpret this finding in terms of knowledge built into the visual system that automatically "infers" the plausible path of motion.

The level-of-analysis view of representation, in which time is thus inside of representation, also leads to a reconceptualization of our immediate experience with the world. If anticipatory computations are part of the reality we represent, one might say that the mentally represented world is constantly falling forward in time.

Hunch 2: Time allows an easy isomorphism between the internal and external worlds.

I have suggested that dynamic representations make good sense. It seems highly advantageous to be able to perceive certain events and make anticipatory computations concerning them. Any creature interacting with the physical world would be aided by a dynamic analysis in which the future was represented mentally.

There may be additional advantages to dynamic representations. In particular, time is unlike all other physical dimensions, in that it may be especially well suited for a simple isomorphism between the internal and external worlds—time may represent time. Shepard (1981) distinguished between simple, first-order isomorphisms and second-order isomorphisms in representation. He argued that in certain domains first-order isomorphisms are unlikely: When we represent the color green in the world, our neurons don't turn green. Shepard prefers second-order isomorphisms for domains like color. These isomorphisms are characterized by a correspondence between perceiving the world and representing the world. In the perception of a real-world rotation, for instance, the mind represents the spatial continuity of the rotation. When we imagine a rotation, the mental representation similarly reflects the spatial continuity of physical rotations.

Although early visual processing (in which retinotopic maps are used) may be characterized by a simple isomorphism of spatial dimensions, at least, it is unlikely that later cognitive processing of the world includes many first-order isomorphisms for most real-world dimensions. The dimension of time, however, seems inherently well suited for a simple isomorphism between the internal and external worlds. This is not to say that there may not be scaling factors between event time and represented time, but instead to suggest that a one-to-one correspondence may sometimes exist.

The proposition that mental time is simply isomorphic with external time is consistent with the "continuity" criterion proposed for dynamic representations (Freyd 1987). But whereas in the past I have been careful to leave open the possibility that the mental temporal dimension might be something other than time (yet that shares inherent constraints with time), I now lean toward the proposition that time represents time. Even more than that, I now speculate that time may represent aspects of other dimensions. For instance, the continuity of time may allow us to represent continuity along a variety of continuous dimensions in the world, by avoiding the problem of simultaneously representing an infinite number of values with a finite brain (see Johnson-Laird 1983). Time may also do extra mental work for us by implementing the perceptual phenomenon of directionality, even when the directionality relates to a dimension that is not temporal in the world (Freyd and Pantzer 1989).

Hunch 3: Static art points to dynamic representations.

Arnheim (1974, 1988) and others have argued convincingly that a key component of art appreciation is the excitement generated by configural tension and other sorts of implicit dynamics. Surely many would agree that painters, sculptors, architects, and now photographers have long exploited the power of implied dynamics. Sometimes the implied dynamics is explicit, as in Michelangelo's David or the dancers in figure 5.7.

In other cases the dynamic tension is more abstract, as in Matisse's paintings, the Sydney opera house (see Arnheim 1988), or figure 5.8. Arnheim argues that dynamic tension in abstract works comes from various configural sources of unbalance. Yet another possibility for the source of dynamic tension in abstract forms (such as the patterns in fig. 5.5) is suggested by a new collaboration I have begun with Geoffrey Miller, in which we are investigating cues of animacy in the dynamics of simple displays. Perhaps arrows and triangles can invoke forward memory distortions (as found by Freyd and Pantzer 1990) and the sensation of pointing, by virtue of activating perceptual representations of animate creatures that have a directionality to them. This may relate to adaptive anticipatory computations if it is the case that animals appear to point in a direction in which they are more likely to move.

In addition to abstract and explicit implications of dynamics in static art, I believe that dynamic tension may come from the medium, too, as in Japanese

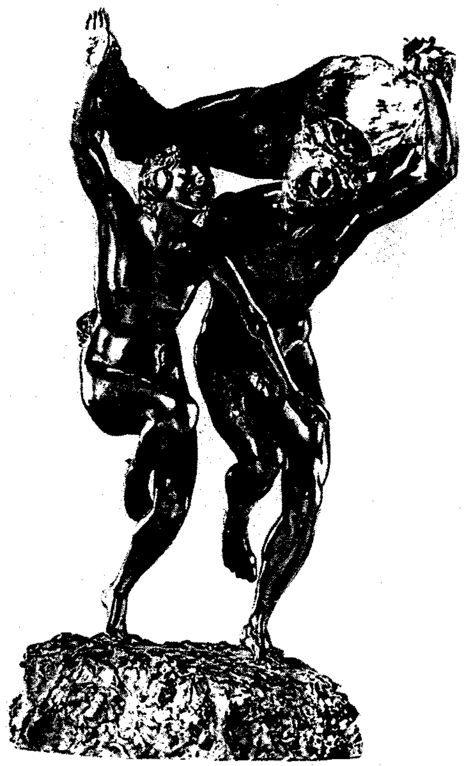

Figure 5.7 An example of explicit implied dynamics in static art: Photograph of Pavlova and Mordkin in "*Bacchanale Russe*," 1912, bronze, by Malvina Hoffman (courtesy of The Fine Arts Museums of San Francisco, gift of Alma de Bretteville Spreckels).

calligraphy, or the paintings of Jackson Pollock, both of which may be perceived partly in terms of the creation process (see Freyd 1983a), or in the figure 5.9 where the contrast of light and dark seems to shimmer almost, or the paintings of Mondrian, where there may be a dynamic tension between the surface of the painting with visible brush marks and the cool geometry of the design (see Freyd 1987).

But given this power of implied dynamics in static art, what is the perceptual basis for the aesthetic experience? The experiments using static pictures (Freyd 1983b; Freyd, Pantzer, and Cheng 1988; Freyd and Pantzer 1989) suggest to me an explicit model for aspects of the perception of art. In those experiments, the retention interval used between the static picture to remember and the test item was in the range of 250–500 ms. That fraction of a second was sufficient to produce a memory distortion.

When viewing a static photograph, observers make a sequence of discrete eye movements (saccades). These eye movements are typically also in the range of 250–500 ms. This suggests to me that when the eye lands on a "dynamic" part of the static art (for instance, the top of a Roman column, or a

Figure 5.8 An example of abstractly implied dynamics in static art: *Orange* (Composition with Chessboard) by Vassily Kandinsky, 1923, color lithograph (courtesy of The Fine Arts Museums of San Francisco, gift of Mrs. J. Wolf in memory of Miss Rachael Abel).

tensed muscle in a statue, or a thick brush mark on a painting surface) and then moves again to another location, in between those saccades the memory for the first part of the art might be slightly shifted in the direction of the implied dynamics. When the eye then later returns to the spot of dynamic tension, there would likely be a small discrepancy between the memory for that spot and the immediate perception of the information—and this discrepancy may be a source of aesthetic excitement.

Hunch 4: Temporal continuity in representation depends on asynchrony in neural networks.

The continuity criterion for dynamic mental representations might appear incompatible with the fact that in many cases individual neurons fire discretely (Kandel and Schwartz 1985; cf. Requin, Riehle, and Seal, chap. 30). Although cognitive theories are often held immune to consideration of the details of neural implementation, it seems desirable to attempt to reconcile one's cognitive models with what is known about the brain. My hunch is that temporal continuity is achieved, despite the nature of individual neural firings, through the asynchrony that may exist between neural connections working together in a network.

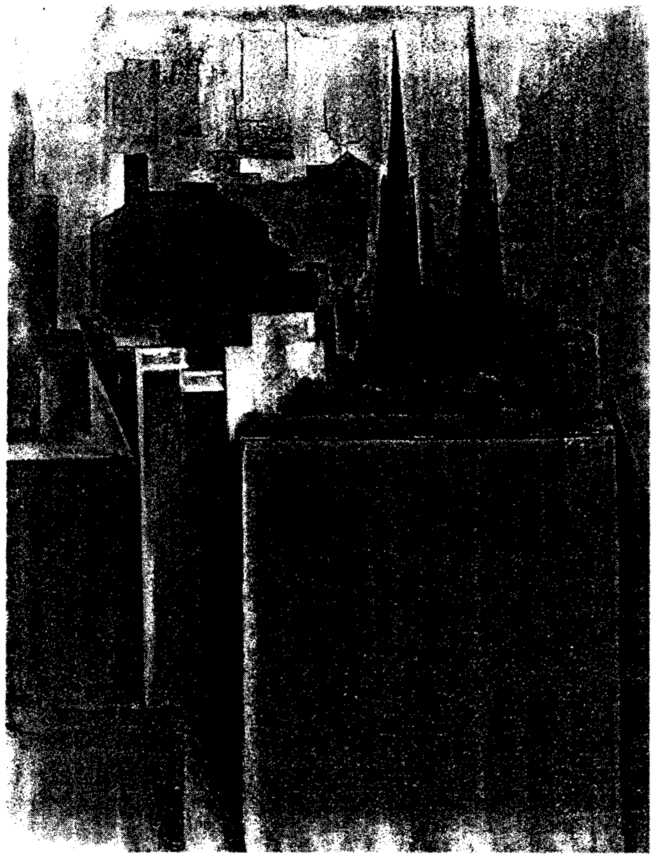

Figure 5.9 An example of dynamics implied by the medium used in static art: *New York Rooftops*, by Georgia O'Keefe, 1925–1930, charcoal on laid paper (courtesy of The Fine Arts Museums of San Francisco, Achenbach Foundation for Graphic Arts, gift of Mrs. Charlotte Mack).

An underlying continuous system is supported by empirical results in cognition, perception, and motor behavior (Freyd 1987; Shepard and Cooper 1982), and neuroscience (e.g., Georgopoulos et al. 1989; Poggio 1984). At the neural level, a number of interesting phenomena seem to depend on phase differences between the firings of groups of neurons (Freeman 1981; Gerstein 1970; Toyama, Kimura, and Tanaka 1981). At least one neural computational device is known to depend on a kind of orchestrated synaptic asynchrony. Sound localization in the barn owl involves a brain nucleus to which neurons from each ear enter at opposite sides and interdigitate through dendritic connections. The cells in this region then discharge maximally when inputs from the two sides arrive simultaneously (Takahashi 1989). Thus, predictable temporal asynchrony in dendritic transmissions underlies this computational device.

Some current connectionist networks approximate continuity not through asynchrony but through a range of values associated with neural activations that are synchronously and uniformly updated (see Jordan 1986; Smolensky 1988). Discrete time slices and a global clock are computationally convenient. Analysis of distributed processing systems without global clocks is much more difficult than reasoning about synchronous systems (Lamport 1978). Since any continuous process can be modeled discretely without detection depending on the resolution of the measurement instrument, current PDP models might be highly compatible with my continuity criterion if the cycle time of the model is not constrained by biological data. Further, a description of networks that approximates continuous activation updates in discrete time slices may be a good approximation to a formal description of neural networks that assumes discrete firings distributed continuously and stochastically over time. If the activation level of a processing element is reconceptualized as its expected value, for instance, the two models may prove identical under some conditions.

It is likely, nonetheless, that there are subtle differences between these synchronous and asynchronous models; for instance, the probability distribution around the expected value of a processing element may depend on whether we assume discrete but asynchronous firings or continuous activation values. A synchronous firing model makes modeling of phase relationships between neuronal responses awkward. More important, allowing for asynchrony in the firing of individual processing elements permits parsimonious models where information is carried not directly by patterns of activation but by their emergent rhythmic patterns of activity (Shastri and Ajjanagadde 1990). Shastri and Ajjanagadde, in fact, present a model in which asynchrony coupled with phase drift predict bounds on the number of items in short-term memory.

While awaiting more formal investigation of asynchronous PDP systems, connectionist modelers should at least be alert for artifacts caused by the temporal resolution they happen to choose.

Hunch 5: Shareability may constrain dynamic mental representations.

How can humans mentally represent the vast complexity and continuity of the world when necessary for perception and action, and at the same time represent a world simple enough to allow conscious thought and communication? I've already pushed the notion of dynamic mental representations as a way to handle the vast complexity and continuity of the world when necessary for perception and action. But are dynamic representations conducive to information sharing? Are they even available to conscious thought?

Shareability (Freyd 1983c, 1990) is a theory about knowledge structure and mental representation that considers the consequences of the fact that humans depend heavily on the sharing of information. Shareability claims that at least some of the properties we observe in knowledge structures emerge during the sharing process and specifically do not directly reflect inherent constraints on individual minds. This theoretical position is at odds with the viewpoint, dominating most of linguistics and cognitive psychology, that observed structure directly reveals innate or learned constraints of the human mind. Shareability does not deny that ultimately the constraints have their roots in the individual mind, but it claims that there are emergent properties that are qualitatively unique to the process of information sharing.

The shareability constraint that I have been most interested in pursuing further is that shared information becomes more categorical than it is when originally represented in the individual mind. I believe this claim touches on a basic and fundamental problem in psychology: What is the basis of categorization? The accepted position in the field is that the need and the ability to categorize information stem from the individual (e.g., see Pinker and Bloom 1990). Shareability is an alternative position, which claims that in some situations at least, categorization takes place only because information is shared. It occurs because of the greatly reduced channels of information flow between two or more separate minds, in comparison to the representational capacities of the individual mind, combined with the strong pressure to minimize information loss.

Suppose, for instance, that a group of rafters attempt to share information about the properties of currents in a river, for which only some rafters have direct perceptual experience. If each individual's representation of the information includes fine-grained or continuous information about the river currents, there will initially be enormous potential for information distortion when sharing this information over a group of people. However, across time and an increasing number of individuals sharing the information, certain modal values will emerge as anchors within the shared structure (perhaps partly based on mutual knowledge accessed through analogy or metaphor; see Freyd 1983c). The sharing process will thus behave like a discrete filter that is relatively stable across time and space. Similarly, a tacit agreement on a small number of categories along potentially continuous dimensions will minimize increasing information loss. Even without such agreement, shareability predicts that there will be convergence on modal values (Freyd 1990). In other words, the fine-grained or continuous information is traded for stability over time and space.

Shareability predicts that private knowledge is often represented with dimensions that capture the continuous structure of real-world dimensions, but that shared knowledge is constrained by properties that emerge in communication (such as limitations of the communication medium and the pressure to minimize information loss), so that shared knowledge is represented with dimensions in which underlying continua are partitioned into discrete categories. The theory of dynamic mental representations proposes that for perception and related processes, the temporal dimension in the representations does reflect the continuous structure of time in the real world. This proposal, taken together with shareability, predicts that dynamic mental representations are not directly shareable and that, in particular, the continuity of the temporal dimension may be lost in shared knowledge. If we further suppose that our most consciously accessible representations are already in a format appropriate for sharing, this might explain why the hypothesis that representations are dynamic seems at odds with conscious experience.

Although I have argued that the continuity of a temporal dimension is basic to representations serving much of cognitive processing, such as perceptual processing, the continuity property may be limited to only some cognitive modules. It might make sense, for instance, to quantize the temporal dimension in conscious representations, assuming that the representations serving consciousness have evolved to be most shareable (given that we are a social species). It may even be that continuity is limited to the module in which the representation resides; that is, it may be that continuous information is not shareable from module to module within the individual mind. In other words, module-to-module communication might lead to a kind of shareability within the mind (Freyd 1983c).

The possibility that continuity and discrete categories both exist due to the contrast between nonshared and shared mental processing units (whether we consider the units to be individual brains or individual modules within a brain) may shed some light on the mixed empirical evidence on how discrete versus continuous are mental representations. The mixed empirical evidence has fueled many debates, including some current controversy surrounding connectionist versus symbolic models of cognition (e.g., see Pinker and Prince 1988). Perhaps mental representations are continuous within an individual brain or individual brain module, but at larger levels of interaction and analysis, shareability has the effect of partitioning that continuity into discrete categories.

Shareability predicts that analyzable constraints will emerge when knowledge is being shared. It is likely that such constraints would have an effect on dynamic information, for such information is considered continuous, and shareability predicts that underlying continua will be represented as categories. The existence of qualitatively different sorts of mental representations may account for our ability to represent, when necessary for perception and action, a great deal of the complexity and continuity of the real world, and also for our ability to represent the world with sufficient economy and simplicity so that when necessary we can communicate our knowledge about the world.

5.4 CONCLUDING REMARKS

Five new hunches have been proposed based on earlier empirical and theoretical work on dynamic representations. Hunch 1 takes the importance of time in human cognition toward a monistic view of the structure/process dichotomy such that the study of mental representations refers to a level of analysis of mental mechanisms. This level addresses the relationship between information in the mind and information in the world. Hunch 2 proposes that mental time represents time in the world (and the anticipated world).

Hunches 1 and 2 thus pursue the implications dynamic information has for theories of representation at the cognitive level. Hunch 3 is a proposal for a new empirical application of dynamic representations—the perception of motion in art—and a proposal for a cognitive computational model that might underly aspects of aesthetic excitement. Hunch 4 moves "down a level" and considers issues related to the neural basis of dynamic representations. Hunch 5 moves "up a level" by addressing the discrepancy between internal dynamic representations and representations that people share with one another.

Each of these hunches is speculative by nature; it is hoped that at least one hunch is pointing in the right direction.

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