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DYNAMIC REPRESENTATIONS GUIDING ADAPTIVE BEHAVIOR

J. J. FREYD
Department of Psychology
University of Oregon
Eugene, OR 97403
USA

ABSTRACT. We plan and execute our own actions while other animals, people, vehicles, and objects move around us. Our survival depends on the success of these daily interactions with a dynamic environment. It is thus highly advantageous to anticipate the movement of other creatures and objects in relation to our own future states. Even if we are planning to walk around or lift up an object currently at rest, we need to anticipate the effect of our motor movements on the environment. The advantages to anticipating movement suggest that representations of the world emphasize the future. I will review empirical support for my theory of "dynamic mental representations" with a focus on the implicit perceptual knowledge we have of dynamics and biomechanical motion. I will suggest that time represents time, and that therefore the normal view that representations are in some way distinct from processes is incorrect. Instead, I will argue, mental representations are an emergent property of processes unfolding over time. In this view, "representation" refers to the correspondence between internal and external information. Temporal information about the immediate future is of primary significance to our motor success, and thus to the human mind.

1. Introduction

In everyday encounters with the world we interact with a dynamic environment. And we are ourselves moving creatures. Whether driving on the Autobahn, playing soccer, feeding an infant, hunting foxes, or fleeing polar bears, we must coordinate our movements with the movements of other moving beings. Even if the current environment contains no active objects besides ourselves, we may be planning to act on the environment, by walking through it or by manipulating an object within it.

I theorize that perceptual representations are *dynamic* (Freyd, 1987) and that static stimuli invoke dynamic mental representations. I will propose that the advantages to anticipating movement suggest that *representations* of the world emphasize future time. This viewpoint suggests that the mental representation of the external world is sometimes "ahead" of external time.

I will review empirical support for my theory of "dynamic mental representations" emphasizing the domains of picture perception, representational momentum, and apparent motion. After reviewing the empirical results I will discuss criteria for dynamic representations, with a focus on the continuity criterion. Next I will suggest that *time represents time*, and that therefore the normal view that representations are in some way distinct from processes is incorrect. Instead, I will argue, mental representations are an emergent property of processes unfolding over time. In this view, "representation" refers to the correspondence between internal and external information. Temporal information about

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the immediate future is of primary significance to our motor success, and thus to the human mind.

2. Empirical Support for Dynamic Mental Representations

2.1. PAST AND FUTURE: HANDWRITING RECOGNITION AND PICTURE PERCEPTION

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, 1983b; Freyd, 1987; Watt, 1980). If so, our ability to decode handwritten material may partly depend on our knowledge of how the material was created.

Figure 1. A "frozen-action" photograph.

Freyd (1983b) 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 (DeKay & 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 superficially static.

My answer to Question #2 invoked the future. Consider one sort of static picture that can imply motion — snap-shots of objects and creatures captured in the middle of an event (see Figure 1). I hypothesized that people might perceive implicit motion when presented with such pictures of "frozen" motion 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-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 memory, and then to view a second picture and decide as rapidly as possible whether the second frame was "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.

2.2. REPRESENTATIONAL MOMENTUM

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 & 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 & Finke, 1985), subjects were presented with a static figure in a sequence of orientations sampled from a possible path of rotation (see Figure 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 (Cooper, Gibson, Mawafy, & Tataryn, 1987; Freyd & Finke, 1984; Freyd & Finke, 1985; Freyd & Johnson, 1987; Kelly & Freyd, 1987; Verfaillie & d'Ydewalle, 1991) have been discovered for implied translational motion (Finke & Freyd, 1985; Finke, Freyd, & Shyi, 1986) and for an implied spiral path (Freyd & Taylor, 1990). When the transformation is subjectively continuous (as in animation), the memory displacements may be even bigger (Faust, 1990; Hubbard, 1990; Hubbard & Bharucha, 1988) 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).

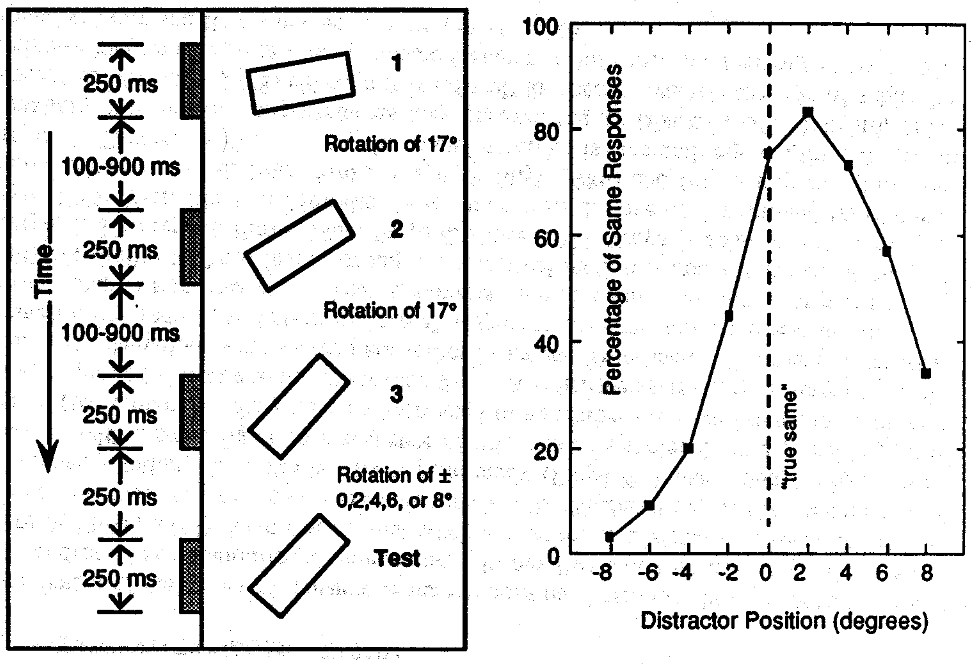

Figure 2. Schematic depiction of stimuli and results from a representational momentum experiment (Freyd & Finke, 1985)

Finke and I termed this phenomenon "representational momentum" (Freyd & Finke, 1984) because of its similarity to physical momentum, in which a physical object continues along its path of motion due to inertia. As with physical momentum, representational momentum is proportional to the implied velocity of motion (Finke et al., 1986; Freyd & Finke, 1985), and also varies with the implied acceleration (and thus implied final velocity) of the pattern (Finke et al., 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 & Johnson, 1987). It also is impervious to feedback or practice (Finke & Freyd, 1985). Furthermore these parametric effects have been demonstrated in a non-visual domain: Using sequences of pitches, Kelly, DeKay, and I (Freyd, Kelly, & DeKay, 1990; Kelly & 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 & Finke, 1984; Freyd & Johnson, 1987; Freyd et al., 1990). When the shapes of objects are radically altered from item to item in an implied rotation momentum effects do not emerge (Kelly & Freyd, 1987). And when the inducing display ends with an implied final velocity of zero, the momentum disappears (Finke et al., 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 & Freyd, 1987).

2.3. THE INTERNALIZATION OF TIME AND COGNITIVE PENETRABILITY

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 (Finke & Freyd, 1989; Freyd, 1987). 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, may be a necessary product of the adaptive advantage of anticipatory computations and a more general internalization of time (see Figure 3).

Of relevance to this interpretation of representational momentum is evidence that the phenomenon is apparently not particularly cognitively penetrable (Finke & Freyd, 1989) The memory task offers subjects an objective correct answer, and obtaining that correct answer requires that subject refrain from transforming the stimuli to be remembered. Moreover, despite practice and feedback the effect persists (Finke & Freyd, 1985).

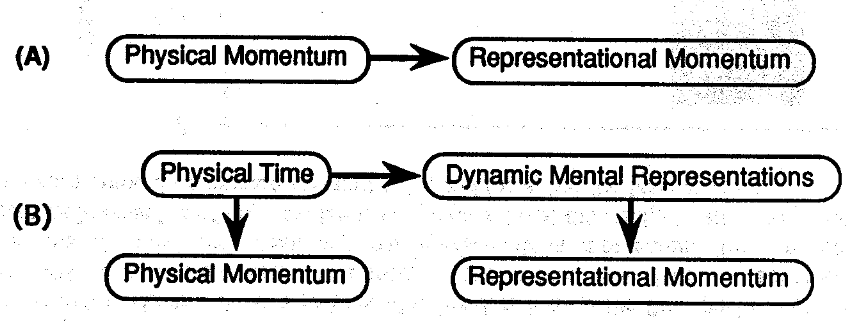

Figure 3. Representational momentum, rather than (A) being directly adaptive, may be a (B) necessary product of the adaptive advantage of anticipatory computations and a more general internalization of time (Freyd, 1987; Freyd et al., 1990).

2.4. CURVILINEAR MOMENTUM

The divergence between representational momentum and purely physical momentum is also indicated by Taylor's and my investigations of momentum for an object travelling through a spiral tube (Freyd & Taylor, 1990).

At the start of each trial subjects were presented with a hollow spiral tube displayed in the center of a graphics screen (see Figure 4). Based on instructions used in naive physics experiments (McCloskey, 1983), subjects were told: "You will see a spiral tube on the screen. Imagine that you are looking down on the tube and that it is made of metal. A metal ball will enter one end of the tube and exit the other end of the tube."

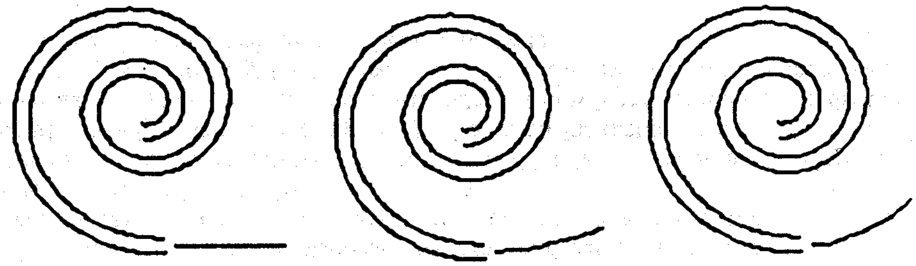

Figure 4. The spiral tube used to investigate representational momentum of curvilinear momentum (Freyd & Taylor, 1990). The three lines at the exit of the tube represent, schematically, the three possible paths of motion the exiting ball might take.

After pressing the foot pedal, a ball appeared at the center of the spiral tube and travelled through the tube. The last position of the ball was outside the spiral tube by a small amount. Depending on path condition, that final position was either on a spiral, curved, or straight path from the exit position . After a 150 ms stimulus duration for the final position of the ball, the screen was cleared. Then there was a short retention interval — 150 ms — followed by a test ball in one of 5 positions. Assuming that representational momentum effects reflect accurate perceptual knowledge of physical laws, we predicted that the straight path would should show the greatest amount of forward memory shift, and the spiral the least amount.

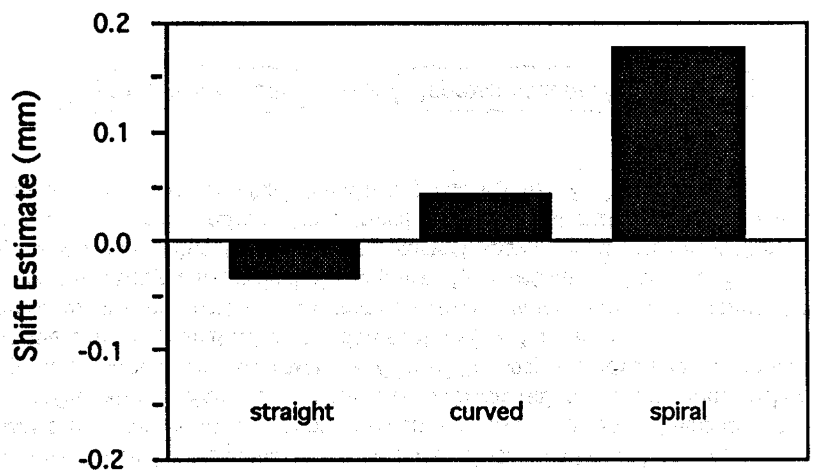

Figure 5. Results from the spiral tube experiment (Freyd & Taylor, 1990).

However we found just the opposite (see Figure 5). Why is this? Most of the moving objects with which we interact are animate, not inanimate. Thus our anticipatory computations may reflect built-in assumptions of future motions that are appropriate for animate creatures, not inanimate objects. Geoffrey Miller and I (Miller & Freyd, In preparation) recently have found that representational momentum effects are especially pronounced for displays of apparently animate creatures, as compared with more abstract control displays (see Figure 6). Perhaps certain naive physics errors arise from assumptions of animacy. Animate creatures do have internal sources of force, so curvilinear motion in the absence of external force is not a problem.

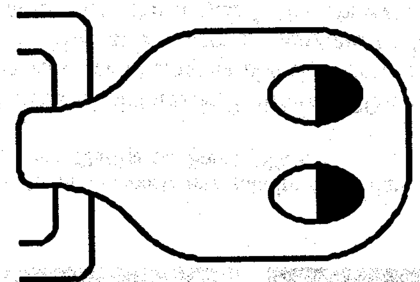

Figure 6. An "animate" stimulus icon similar to those used in experiments investigating representational momentum for apparently animate versus inanimate moving shapes. (Miller & Freyd, In preparation)

2.5. APPARENT MOTION OF THE HUMAN BODY

Evidence about the nature of dynamic representations and knowledge of biomechanical motion also comes from studies Maggie Shiffrar and I have conducted on apparent motion (Shiffrar & Freyd, 1990; Shiffrar & Freyd, 1991). In classical demonstrations of apparent motion, two spatially separated objects are sequentially presented within a certain temporal range. The visual system interprets this pattern as arising from a single moving point. The constructed motion is one interpretation out of an infinite possibility of motion interpretations. For instance, in constructing motion between the simplest of two displays, a dot first shown in one place and then in another, the visual system constructs only one motion path out of an infinite number of motion paths. How does the visual system select or construct a particular path? Why is one path preferred over another? It was believed until very recently that only constraints such as rigidity and shortest path would determine the interpolated path: But consider biological motion: It often violates constraints of rigidity and shortest path. Yet is has clear ecological consequence to the perceiver. We know from research using point-light displays that human adults are sensitive perceivers of biomechanical motion (Johansson, 1975) as are human infants (Bertenthal, Proffit, & Cutting, 1984).

We thus hypothesized that with high-quality photographs of the human body in different poses, and with sufficient processing time, the interpolated motion paths will be consistent with anatomically possible motion even if that motion is not the simplest, or shortest, rigid displacement. In one experiment observers viewed alternating photographs of a human body such that apparent motion was experienced. The photographs were chosen so that anatomically correct motion was pitted against shortest path. We considered two anatomical constraints: the joint constraint and the solidity constraint (see Figure 7). For joint constraint stimuli, the shortest rigid path was impossible given human joint mechanics. For the solidity constraint stimuli the shortest rigid path would require one part of the body to pass through another part of the body.

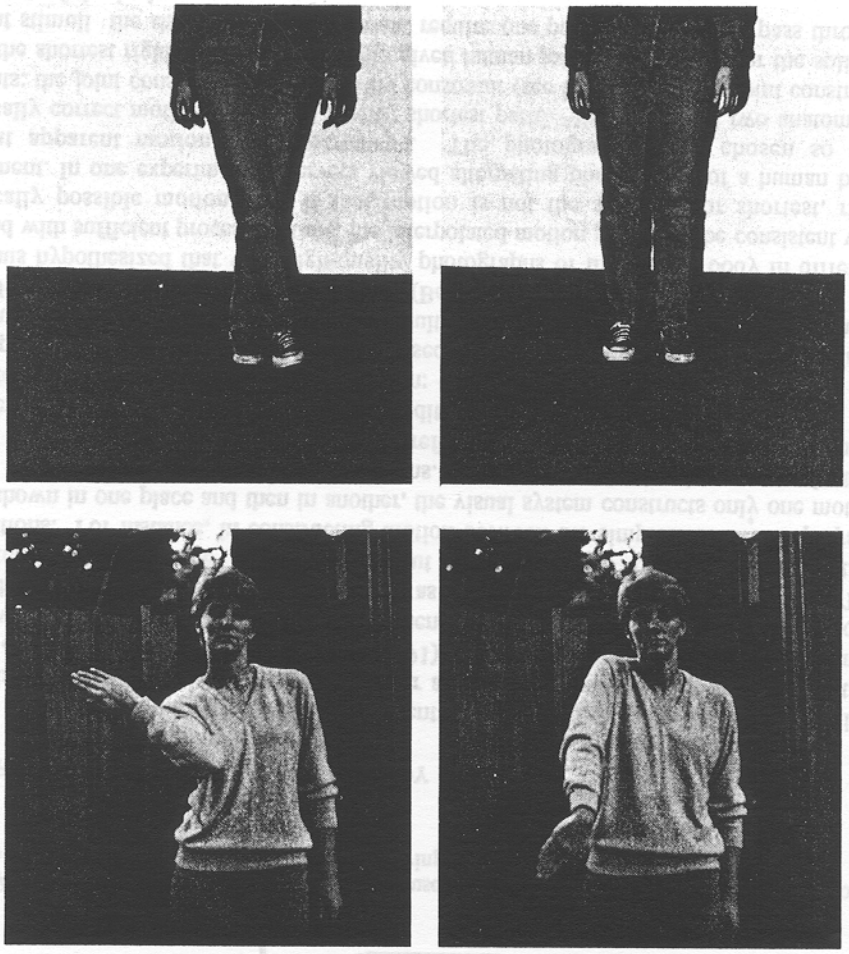

Figure 7. Two pairs of stimuli demonstrating solidity constraints (top) and joint constraints (bottom). Reprinted with permission from Shiffrar and Freyd (1990).

Observers saw 15 pairs of pictures at 7 different SOA settings. For each SOA setting subjects were asked to view the alternating photographs and then to indicate the motion path they experienced by looking at a schematic diagram of the possible paths. The results confirmed our hypothesis that with longer SOAs observers report experiencing the longer path lengths (see Figure 8). We have since replicated these results and run a series of control experiments (Shiffrar & Freyd, 1991). The results to date all point to the significance of knowledge of biomechanical motion constraints. I believe these results suggest that our dynamic representations are tuned toward laws of animate motion.

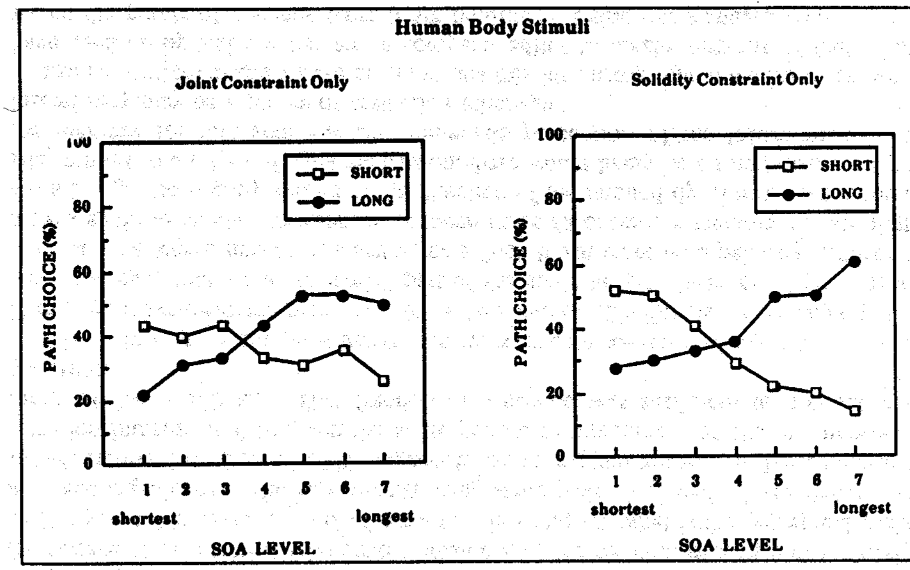

Figure 8. Results from Experiment 1 (Shiffrar & Freyd, 1990) divided according to stimulus type. On the left are the results from five pairs of joint constraint stimuli. On the right are those from ten pairs of solidity constraint stimuli.

2.6. STATICS AS FORCES IN EQUILIBRIUM

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 followed by a depiction of the same scene suddenly in disequilibrium but without any change in position of the to-be-remembered object. Subjects made more memory errors in the direction predicted by the disequilibrium than in the opposite direction. This result suggests that lurking behind the phenomenal sense of concreteness one has when viewing some pictures or scenes may be an underlying representation of physical forces.

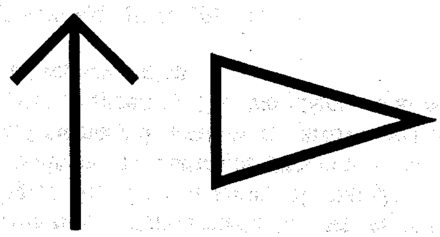

Figure 9. Simple static patterns like arrows and triangles appear to point.

Freyd and Pantzer (Freyd & Pantzer, In preparation) recently investigated the dynamics of simple static patterns. Some simple static patterns like arrows can produce a compelling sense of directionality (see Figure 9). 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.

2.7. DYNAMIC ASPECTS OF ART PERCEPTION

Arnheim (1974; 1988) and others have argued that a key component of art appreciation is the excitement generated by 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*. In other cases the dynamic tension is more abstract, as in Matisse's paintings, of the Sydney opera house. Arnheim (1988) 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 is suggested by the work I reviewed on perception of animate motion. Perhaps arrows and triangles can invoke forward memory distortions and the sensation of pointing, by virtue of activating perceptual representations of animate creatures which 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 that 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 calligraphy, or the paintings of Jackson Pollock, both of which may be perceived partly in terms of the creation process (Freyd, 1983b), 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.

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, 1983a; Freyd & Pantzer, In preparation; Freyd et al., 1988) suggest to me an explicit model. 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. 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 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.

Donna McKeown and I have begun to test this idea using reproductions of art works. We have used an optical scanner and a computer editor to create versions of these painting in which the points of dynamic tension are modified. Using our standard memory test, we've been able to show forward memory distortions at those points. Our next step is to attempt to relate the memory distortions to both judgements of aesthetic excitement and spontaneous eye movements.

3. Theoretical Implications

3.1. DYNAMIC MENTAL REPRESENTATIONS AND THE CONTINUITY CRITERION

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 (Freyd, 1987): I) A dynamic mental representation is one in which the temporal dimension is inextricably embedded in the representation. It is mandatory, necessary, and unavoidable. II) The internal temporal dimension is inherently like external time (at least to a first approximation). Regarding the second criterion, 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. (1) The temporal dimension must be directional; the external time humans confront goes forward. (2) The temporal dimension must be continuous (or as continuous as the mechanics of neural networks permit). Operationally, continuity will mean that between any two points of time, another point of time exists.

The continuity criterion is particularly relevant to my current thinking about dynamic representations. I will briefly describe the experiment on representational momentum that I think supports the continuity criterion most compellingly . Experiment 1 of Freyd and Johnson (1987) used a standard inducing sequence of three rectangles. 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.

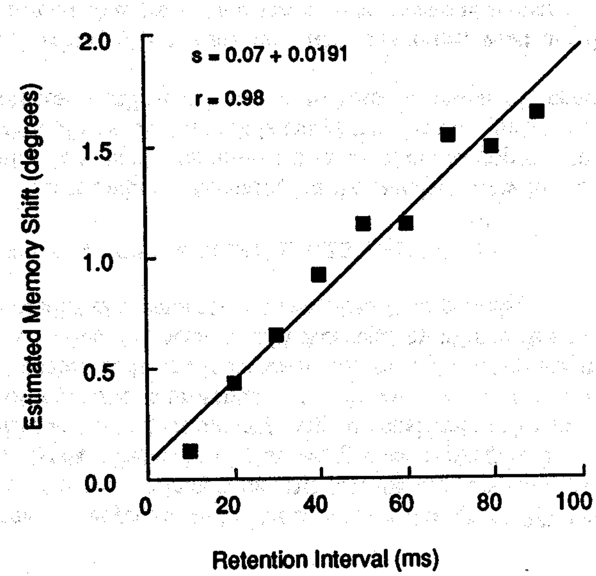

Figure 10. Relationship between retention interval (10-90 ms) and memory shift found by Freyd and Johnson (1987).

We found an approximately linear relationship (r = .98) between these variables (see Figure 10). Other experiments indicate that the memory shift grows for at least the first 200 ms for the standard inducing display using three rectangles. 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.

3.2. A PROCESS VIEW OF MENTAL REPRESENTATION

What *is* a representation? According to the standard view in cognitive psychology a mental representation is a mental thing — a data structure, as opposed to a mental process. Perhaps this definition of representation falls out of the computer metaphor. Whatever its genesis, the structure/process dualism has tended to force a notion of representation that is implicitly static.

If mental representations are not static structures, what are they? My proposal is that mental representations are — in essence — an emergent property of mental processes. To ask about representation is to speak at a particular 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 focussed 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 we also consider what might be called the "why" question: 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. The advantages to anticipating movement suggest that representations of the world might emphasize future time. 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 be easily represented.

In addition, time is unlike all other physical dimensions, in that it may be especially well suited for a simple isomorphism (Shepard, 1981) between the internal and external worlds — time may represent time. The level-of-analysis view of representation, in which time is thus inside of representation, thus 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.

4. Summary

In conclusion, then, we plan and execute our own actions while other animals, other people, vehicles, and objects, move around us. Our survival depends on the success of these daily interactions with a dynamic environment. It is thus highly advantageous to anticipate the movement of other creatures and objects in relation to our own future states. Even if we are planning to walk around or lift up an object currently at rest, we need to anticipate the effect of our motor movements on the environment.

The advantages to anticipating movement suggest that *representations* of the world emphasize future time, such that the mental representation of the external world is sometimes "ahead" of external time. Even when the representation is "on time" this requires an anticipation of the future by at least a fraction of a second in order to counter-act processing lags due to sensory information transduction within the sensory organs and nervous system. (I speculate that we anticipate the future at a range of time scales, from the immediate future, as I have focussed on in this paper, up to intervals on the order of minutes, hours, days, years, and even decades. Our ability to anticipate the future may be a hallmark of our species, although some might argue based on the state of the world that humans are not well suited for future anticipations in excess of a few years.)

I propose that mental time represents external time, and that therefore the normal view that representations are in some way distinct from processes is incorrect. Instead, I propose that mental representations are an emergent property of processes unfolding over time. In this view, "representation" refers to the correspondence between internal and external information. Temporal information about the immediate future is of primary significance to our motor success, and thus to the human mind.

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