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Dynamic Mental Representations

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This article pursues the possibility that perceivers are sensitive to implicit dynamic information even when they are not able to observe real-time change. Recent empirical results in the domains of handwriting recognition and picture perception are discussed in support of the hypothesis that perception involves acquiring information about *transitions*, whether the stimuli are static or dynamic. It is then argued that dynamic information has a special status in mental representation as well as in perception. In particular I propose that some mental representations may be *dynamic*, in that a temporal dimension is necessary to the representation. Recent evidence that mental representations may exhibit a form of *momentum* is discussed in support of this claim.

There has been a growing appreciation of the impressive ability that the human mind has for perceiving events that take place over time. J. J. Gibson (1979), Johansson (1975), and others have noted that we are particularly receptive to information contained in patterns of change in the environment, as opposed to *static* information (such as that contained in a snapshot).

In this article I will first propose that people perceive *dynamic information* even when the stimuli being inspected (such as snapshots) are not changing in real time. I will then propose that the importance of dynamic information to perception has implications for mental representation. In particular I will argue that mental representations may sometimes contain a temporal dimension and may thus themselves be dynamic.

Perceiving Transitions

I propose that in perception, acquiring information about transitions between states is as important as acquiring information about the states themselves. I believe that the proclivity people show for picking up transitional information extends to situations in which the stimuli are static. A more precise proposition can be stated as follows: When the perceptual system cannot directly perceive change over time it will seek out implicit evidence of change. There are at least two types of implicit change: (a) future change, such as spatial transformations an object can undergo or the continuation of motion in objects captured in a frozen-action photograph, and (b) change that creates an object, such as certain sequences of drawn strokes that lead to a handwritten letter. The proposition argues for the deepening of the perception of a static form by the representation of dynamic information about its possible past and future.

Perceiving Real-Time Transitions

One reason for thinking that the perceptual system seeks implicit information about change is the now good evidence that the perceptual system has a tendency to pick up information about real-time change. For instance, J. J. Gibson (1950, 1966, 1979), Johansson (1950, 1973, 1975), and many others (e.g., Cutting & Proffitt, 1981; Lasher, 1981) have demonstrated the perceptual system's natural competence with information carried dynamically.

This recent appreciation for humans' responsiveness to real-time change relates to a new understanding of perception, not sensation. At the level of sensation it is change in the environment that is detected for any sense (see Boring, 1942). The newer position (which has, of course, old roots; see Cutting & Proffitt, 1981, for discussion), that dynamic information is primary to the perceptual system, refers to higher level perceptual organization. This position could be true or false independent of sensory dynamics.

Among the many studies demonstrating the perceiver's competence to pick up real-time change and to parse the world into *events* that extend over time (e.g., Johansson, 1950) are some studies demonstrating that dynamic information may be relevant in cases where it was previously thought that mainly static information was used. I consider these studies especially relevant to my claim that sensitivity to transitional information extends even to situations where real-time change is not present, because they suggest that dynamic information may be primary to the perceptual system. I will briefly describe examples from three domains of inquiry.

Although investigators usually assume that people recognize an acquaintance by recognizing his or her facial features, body shape, and other aspects of physical appearance, in fact viewers

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can recognize themselves and friends without that configural information if abstract movement information is provided: Cutting and Kozlowski (1977) have shown that a person can be identified in the dark if the person has a small number of tiny lights attached to his or her body and he or she moves. Similarly, some linguistic information can be conveyed, in the dark, to perceivers of American Sign Language if the signer has a few tiny lights attached to his or her fingertips and the hands move (Poizner, Bellugi, & Lutes-Driscoll, 1981). Of course, in these point-light display studies, it is not clear whether subjects use the motion information directly when recognizing friends in the dark or American Sign Language, or whether they use the motion information to infer configural information and then proceed with identification.

Perhaps clearer evidence that the perception of change is fundamental to perceptual organization is the demonstration that one of the important ways that infants determine what makes a given object distinct and unified is by determining what moves as a single object (Spelke, 1982). For instance, in one experiment Kellman and Spelke (1983) habituated infants to a rod that was moved back and forth behind a partly occluding barrier so that each end protruded beyond the barrier. Infants were then presented with the complete rod and the rod with a small gap, moving in the same fashion. Habituation to the moving occluded rod generalized to the moving complete rod but not to the moving rod with a gap. Presented with the same partly occluded rod but without movement, infants did not generalize to the complete rod. Perhaps most striking, when infants were habituated to two different objects (a rod and a polygon differing in color and texture) moving together, their habituation generalized to a connected polygon and bar and not to a polygon and bar separated by a gap. Indeed, this habituation was just as strong as in the experiment with the moving rod. Thus it seems that movement information is more important for perceiving object cohesiveness than unity of shape, color, and texture.

There is also evidence that the perception of transitional information is important in audition as well as vision. The perception of sound, of course, is fundamentally dependent on information that varies over time. Relevant to this article, however, is evidence that higher order transitional information carried in sound is emphasized by the perceptual system. For example, Remez, Rubin, Pisoni, and Carrell (1981) demonstrated the importance of time-varying relations in phonetic perception. They found that the essential features used in perceiving words are determined by the transitions from one phoneme to the other, as opposed to context-independent features of each individual phoneme.

Perceiving Implied Transitions

If the perceptual system is geared to perceive transitions in real time, what might it do when presented with a display that is not changing? I propose that in such a situation the perceiver will seek out implicit information about change. Put differently, if it is found that people do readily perceive implied transitions, there is evidence that the perceptual system is geared to perceive transitions. Thus I believe that the strongest test of the importance of dynamic information to perception is in the case where, technically, no movement is actually present but is in some way nonetheless implicit in the stimulus. The phenomenon of apparent motion is one such situation. However, apparent motion may result from the triggering of motion detectors early on in the visual pathways (see Braddick, 1974, 1980) and is therefore potentially of less interest to my theoretical position. I will discuss two areas of investigation in which there is clearly no sensory basis to the detection of dynamic information when static stimuli are viewed.

Perceiving Dynamic Information During Recognition of Static Handwritten Forms

Traditional *feature analysis* theories of letter perception (for a review, see E. J. Gibson & Levin, 1975), which assume that perceivers recognize a given letter by perceiving its distinctive features (such as whether the letter is symmetric or not, whether it has a left-diagonal line or not, whether the curves are open or closed), do not account well for human handwriting recognition. Not surprisingly, the stimuli used in the development of these theories for both observation and experimentation have primarily been uppercase block letters or artificial characters based on such letters (see, for instance, E. J. Gibson, Gibson, Pick, & Osser, 1962; Pick, 1965). One problem with traditional feature analysis theories when applied to handwriting recognition is that almost none of the typically studied distinctive features such as symmetry and open or closed curves are preserved in handwritten letters, yet people are clearly able to recognize handwritten messages.

An alternative theory of letter perception that can better account for our ability to recognize handwritten letters (especially when they are distorted by other letters before or after them) assumes that recognition mechanisms use information about how letters are formed. Specifically, it may be that perceivers can infer the underlying dynamic pattern of motor movements by applying knowledge of drawing method to the static trace of a handwritten letter. For example, one possibility, based on an analogy to the motor theory of speech perception (see Liberman, Cooper, Shankweiler, & Studdart-Kennedy, 1967), is that the perceiver produces a model of what he or she is perceiving by following production rules. The proposal that people use knowledge of drawing methods in handwriting is also compatible with some of Watt's (1980) ideas on the proper characterization of the alphabet. He talked about letters as being "kinesthetic morphemes" that can be broken down into "kinemes" that are chronologically concatenated.

Three studies (Babcock & Freyd, in press; Freyd, 1983d; Zimmer, 1982) provide evidence in support of the hypothesis that handwriting recognition involves (a) *knowledge* of drawing method and (b) *sensitivity* to information specifying drawing method in the static trace.

In Freyd's (1983d) study subjects were taught an artificial character set in such a way that they knew how the characters were drawn, yet they never experienced drawing the characters themselves. During training, the subjects watched the characters drawn for them on a computer screen. For any one character there were two possible drawing methods, each rendering exactly the same final form; only the order and direction in which the strokes were drawn varied between the methods. After each subject learned the set of characters by one of the two drawing methods, a test was administered in which only static (i.e., already drawn) characters were shown. Some of the static

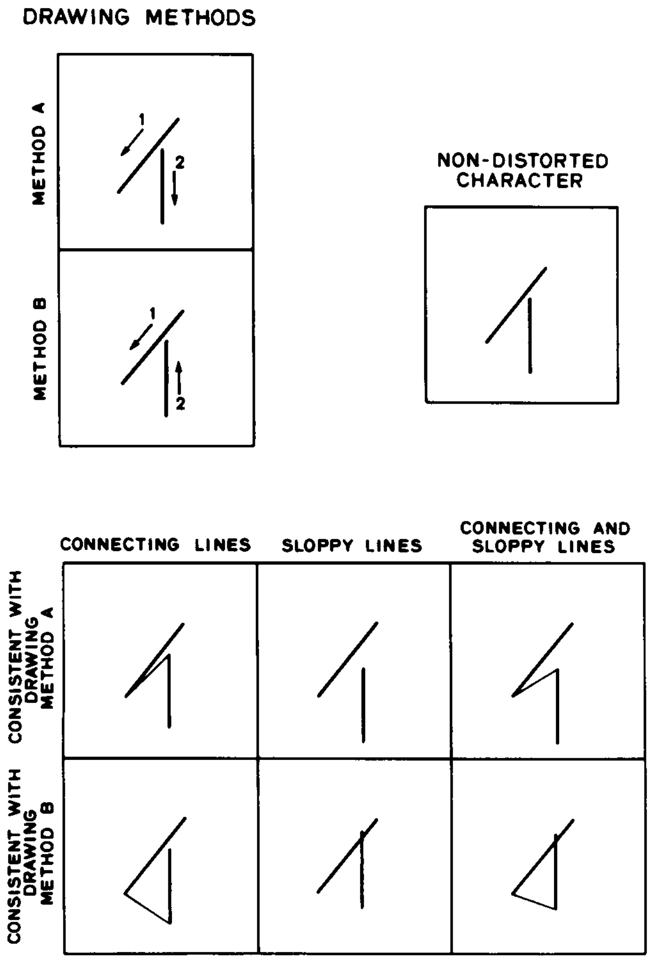

Figure 1. Example stimuli from the handwriting recognition experiment (Freyd, 1983d). (The stroke order—*1* for first stroke—and the stroke direction—associated arrow—are indicated for the two drawing methods used for the example character. The nondistorted test character and the six distortions used in the test are also shown for the example character.)

test characters were slight distortions of the true character. Half of these distortions were consonant with one of the drawing methods, and half with the other (see Figure 1). That is, drawing methods when applied by a human tend to lead to specific types of distortions (e.g., connecting lines between the end of one stroke and the beginning of another), and the predictability of these distortions was used to create the test distortions.

Subjects found the distorted characters that were inconsistent with the drawing method they had learned much more difficult to recognize than either consistently distorted or undistorted characters. For at least one kind of consistent distortion (the sloppy-lines distortion), the characters are easier to identify than for nondistorted characters, presumably because there is information value in the distortion. In a related way, it is interesting that many popular type fonts carry information about a handwriting method, perhaps because that information facilitates letter identification.

The finding that knowledge of drawing method influences the recognizability of distorted characters is consistent with the hypothesis that handwriting recognition is based on tacit knowledge of writing method. This in turn suggests that people can use knowledge of dynamic processes in the perception of static forms. In a second study (Babcock & Freyd, in press) a related hypothesis was more directly tested: that perceivers are sensitive to information in the static trace that specifies the manner in which a character was drawn. We began by creating a new set of characters and inventing two drawing methods for each character. The drawing methods differed in the direction that the last stroke of each character was to be drawn (up or down). We then collected samples of each character drawn by each method (see Figure 2). These samples were used to teach a new group of subjects numerical paired associates for our artificial character set. Half of the subjects were given samples drawn in the "up" manner and the other subjects were asked to learn the characters from the "down" samples.

After training, all subjects were presented with rows of numerals and asked to translate these numerals by writing down corresponding rows of characters. Their writing behavior was monitored during this translation task. In particular, an experimenter noted whether each subject drew the last stroke in an upward or downward direction. In two separate experiments, we found that the probability of drawing the last stroke up or down depended on the drawing-sample set that the subject saw, confirming our hypothesis that people extract information pertaining to drawing method when shown static examples of hand-drawn characters.

Zimmer (1982) also extended the handwriting recognition theory presented in an early draft of Freyd (1983d) by investigating what sort of representation (e.g., static or dynamic) is most effective for mentally representing a letter. He asked subjects to answer questions about the configural characteristics of a given handwritten letter while forming one of mental images. He found that subjects were better able to answer such questions while forming a mental image of the letter being drawn, than while forming a mental image of the static appearance of the letter. This finding adds further support to the notion that knowledge of drawing method is used by recognition processes.

Perceiving Dynamic Information During Perception of Static Pictures

Friedman and Stevenson (1980) have commented that "pictorial movement is compelling, that over and above its informa-

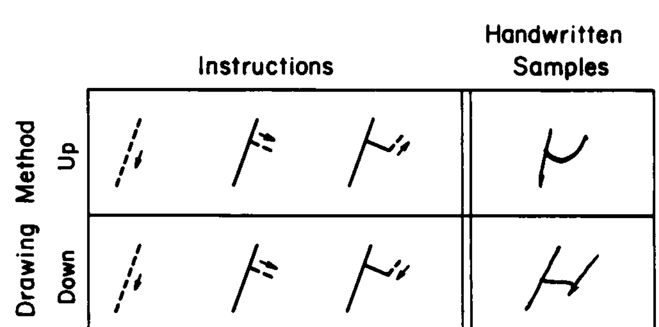

Figure 2. Illustration of the two drawing methods used by Babcock and Freyd (in press) and examples of the distortions each method produces.

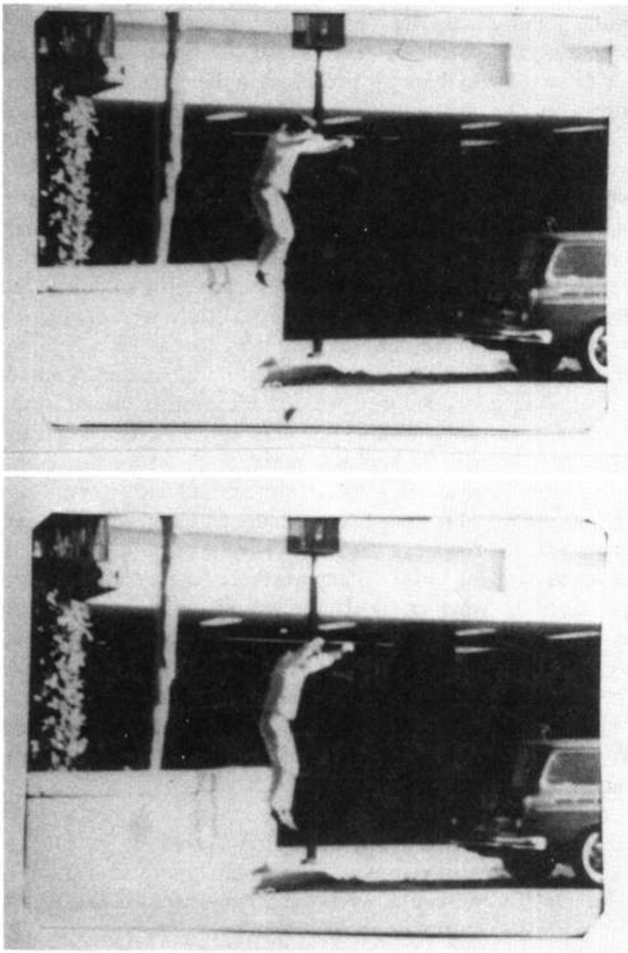

Figure 3. A before (above) and after (below) pair from the action sequence "person jumping off a wall" used in the picture perception study (Freyd, 1983c).

tional value, it can also transmit a sense of movement" (p. 226). Certainly, one situation in which people might represent movement, under conditions that are technically static, arises when viewing pictures that depict motion. For instance, photographs that capture, or "freeze," some object in the process of motion might induce a mental representation of movement.

If so, when a person views a photograph of an object undergoing a unidirectional movement, the person might represent the object as continuing the movement. If this were true, one would expect the person's memory for the photograph to be distorted in the direction of remembering the object as being further along the path of movement. To test this prediction, I first created a set of photograph pairs shot at different times in a sequence as well as an equal number of pairs having the same identical photographs (Freyd, 1983c). Unidirectional action sequences were used, such as a person jumping or water spilling (see Figure 3). I showed one member of the pair to subjects followed by the second. Subjects were asked to decide whether the second picture was exactly the same as the original picture.

Subjects took longer to correctly complete the task when the pair was in real-world temporal sequence than when it was in reverse order, supporting the hypothesis that when people perceive the first member of the pair they cannot help but anticipate the continuation of the implied motion.

The hypothesis that people, when viewing a picture that captures motion, naturally perceive the direction of the motion was further tested using an apparent-motion paradigm (Freyd, 1983c). Visual apparent motion is the perception of motion when the display consists of an alternate presentation of two static stimuli at appropriate time intervals. Usually the critical parameters isolated for seeing motion are time difference between onsets and distance between the stimulus patterns (Kolers, 1972). However, if frozen-action photographs induce a mental representation that partly continues the motion, there should be an asymmetry in the goodness of apparent motion between forward and backward action sequences of the before–after photograph pairs. That is, members of the forward pairs should be a shorter distance from each other in terms of mental representation than members of the backward pairs. When the experiment was actually performed, in which subjects were asked to judge goodness of apparent motion, the forward pair received higher ratings.

Dynamic Mental Representations

Cognitive psychologists have made significant advances in understanding human thinking by investigating the structure of mental representations (e.g., Anderson, 1976; Shepard & Cooper, 1982). In most of this research mental representations have not been considered to be, in any fundamental sense, dynamic (Kolers & Smythe, 1979). This is especially true for theories about the mental representation of objects or categories of objects. For instance, the mental representation of a dog may be described as an image of a typical dog in a canonical orientation (e.g., Kosslyn, 1980), or perhaps as a network of propositions or features (e.g., Anderson & Bower, 1973; Collins & Quillian, 1969). To the extent that our perception and knowledge of even static things depends on our knowledge of dynamic information, one may question how such information is represented in the context of static mental representations.

I will argue that although some sorts of dynamic information can, in principle, be represented in the context of a traditional notion of mental imagery or a propositional model, a more parsimonious solution is to propose that at least some representations are dynamic. The ideas presented in this section are offered not as a complete theory, but as a perspective that might lead to a theory eventually, and may motivate research in the meantime. Similarly, the research results discussed in support of the hypotheses are presented as suggestive, not as definitive.

Toward a Definition of Dynamic Mental Representation

How is a dynamic mental representation different from previous notions of representation? Two definitional criteria are: (a) A dynamic mental representation is one in which time is represented analogically, or using Palmer's (1978) terminology, *intrinsically*. That means that time is represented with a representing dimension that has some of the same inherent structure that real-world time has. (b) A dynamic mental representation is also one in which time is necessarily represented. In other words the representing dimension for time could not be removed from the representation while still preserving any sort of useful representation. Each of these two criteria will be explored in more detail in the following sections.

The intrinsic criterion. Palmer (1978) proposed that a fundamental distinction exists between *intrinsic* and *extrinsic* representation. An intrinsic representation is one in which a *representing* relation (or dimension) has the same inherent constraints as its *represented* relation. (For our purpose representing relations, or dimensions, are in the mind; represented relations, or dimensions, are in the world.) In an extrinsic representation the inherent structure of the representing relation (or dimension) is arbitrary but that of its represented relation is not.

For a representation to be dynamic, two particular aspects of the temporal dimension in our world must also be consequences of the inherent structure of the representing dimension. One of these aspects is that the temporal dimension must be *directional;* time goes forward. The other aspect is that the temporal dimension must be *continuous;* between any two points of time, another point of time exists. (These aspects of time are considered true of the local world we live in, just as space is locally Euclidean; various physical theories about the universe may question the continuity or directionality of time, just as the correct characterization of the geometry of space is questioned.)

One way that both the continuity and directionality of time could be captured by the representing dimension would be if time itself represented the world's temporal dimension. Whereas most researchers would agree that a spatial dimension could not practically mentally represent one of the world's spatial dimensions, thus ruling out a physical isomorphism between space in the world and space represented in the mind, there could, in principle, be a physical isomorphism between time in the world and represented time. Note that even a physical isomorphism allows for differences of scale such that an event that extends over a long time in the world could be represented by a shorter time.

One difficulty with assuming that time represents time arises when trying to account for long-term storage of mental representations. It seems that time would only represent time in "working memory"; thus long-term storage of representations would require some representation of time other than real-world time. This issue will not be pursued further in the present discussion, as the problem is being limited to understanding representing dimensions for active, invoked, mental representations. In a similar spirit, I am not going to try to relate the notion of dynamic mental representations to what might be called "evolving representations," the notion of a memory trace that changes over long periods of time, perhaps because of decay or distortions that occur during the processes or reconstruction (e.g., Bartlett, 1932; Loftus, 1975; Loftus, Miller, & Burns, 1978). These long-term memory effects are interesting but not directly relevant to dynamic mental representations.

Whether the representing temporal dimension is physically isomorphic with time in the world or only "naturally" isomorphic (i.e., inherently structured in the same way; see Palmer, 1978), for a representation to be dynamic it is necessary that the continuity and directionality of time be inherent aspects of the representing dimension. An ordered sequence of static representations can mimic a dynamic representation if the grain of the sequence is sufficiently fine given any particular measurement procedure, yet one would not want to call such a set of representations dynamic. Because there is a clear intuitive difference between a representing system that includes intermediate points between close points (such as the rational numbers), and one that does not include the intermediate values (such as the alphabet that does not include representations for continuously varying phones within a phoneme class), I propose that one should define continuity operationally: For any available measurement procedure, if an intermediate representational state corresponding to an intermediate temporal value can be found between any two other states, then the system is presumed continuous on the basis of parsimony. Eventually, when the resolution of the data is fine enough, the burden of proof moves to the skeptic of continuity. Later in this article I will present evidence for intermediate states of represented information with temporal intervals of 10 ms (Finding 9); I think that most would agree that by psychological processing standards, differences of 10 ms reflect a very fine resolution.

Interestingly much of the research that has been taken to support the position that space is represented in a continuous fashion can be taken to even more strongly support the position that the representing temporal dimension is continuous. I am referring particularly to the work on mental rotation by Shepard, Cooper, and their colleagues (e.g., Cooper & Shepard, 1973; Shepard & Metzler, 1971). Although many have focused on the finding that the time to mentally rotate an object is proportional to the angular disparity between the starting and ending positions (a spatial measure), I am currently more interested in the interpretation of the finding in terms of time: The time to mentally rotate an object is proportional to the time it would take to rotate an object in the world.

The most relevant finding from the mental rotation literature for my interests is Cooper's (1976) demonstration that when subjects are probed while engaged in mentally rotating an object from one position into another, they behave as if the object is represented in the expected (given the probe time) *intermediate* position. This is consistent with the claim that if a dynamic mental representation is probed between any two points in time, an intermediate state of the representation should be discovered.

A different sort of finding that satisfies the *continuity* criterion is evidence that a constant acceleration, as opposed to velocity, can be constructed by the subject in an apparent-motion task (Freyd, 1983a). I showed subjects a display in which a bar was sequentially presented in a progression of locations across a screen. The spatial and temporal intervals were chosen so as to produce apparent motion of a bar sweeping across a screen. When the spatial separations were held constant but the temporal locations were successively shortened or lengthened, subjects could, in principle, see either a continuous constant acceleration or a step-function sequence of increasing or decreasing velocities. In an adaptation of a technique introduced by Robins and Shepard (1977), subjects were probed with a small dot that appeared on the path of the apparently moving bar; they were asked to indicate whether the dot appeared before or after the bar. By comparing their responses under different timing conditions, the researchers obtained some evidence regarding the way in which subjects represented the movement. The results indicate that people do represent constant acceleration under appropriate conditions. The ability to represent this continuous change of rate, assuming that it exists, is difficult to account for with static representations that must then be transformed over time at a changing rate, because it has been assumed that transformation rates are due only to limitations on processing the representation. Dynamic mental representations, however, would include time as part of the representation and are thus easily modeled as changing at arbitrarily complex changing rates, that is, changing continuously.

The "necessary" criterion. The second criterion proposed for determining whether a representation is dynamic involves the notion that a temporal dimension is *necessary* to the representation.

Kubovy (1983) has pointed out that the mental rotation of objects has typically been talked about in terms of "rotating mental images," when it might be preferable to talk, instead, about imagining the rotation of the object. For slightly different reasons, I have also proposed (Freyd, 1983a) that it is preferable to talk about "imagining transformations" as opposed to "transforming images." One thing at issue here is the role time is assumed to play in observed phenomena of mental imagery. The traditional interpretation of time in mental imagery studies seems to place time on the outside on the representation; that is, temporal effects such as rotation rates or scanning rates (e.g., Kosslyn, Ball, & Reiser, 1978) are considered to stem from constraints on processing the spatial information represented in the image. However, as conceived here, on the basis of the necessary criterion for dynamic mental representations, time is on the inside of the image; it is part of the representation; thus rotation or scanning rates are considered to reflect properties of the representation itself.

One consequence of the necessary criterion when applied to mental imagery is that time becomes coupled with the spatial dimensions in the representation. This proposal is somewhat at odds with the accepted view of time in most theories of representation. For instance, Shepard (1981) distinguished the complementarity between objects and representations from the complementarity between internal and external transformations. Indeed, a structure–process distinction is common throughout cognitive psychology, yet there may be occasions in which processes are simply part of the structure. (Proposing that time may be a structural dimension is different from saying that under some conditions a structural model is formally equivalent to a process model. In the former case the structure itself is considered dynamic; in the latter case a process model can be formulated to predict the same outcome as a structure model.) Although there may be dynamic mental mechanisms that are best considered processes, such as the mechanisms that search memory and retrieve an item for conscious use, there may also be dynamic structures. As Jones (1976) stated,

> humans are built to detect real-world structure by detecting changes along physical dimensions (i.e., contrasting values) and representing those changes as relations (i.e., differences) along subjective dimensions. Because change can only occur over time, it makes sense that time somehow be incorporated into a definition of structure. (pp. 328–329)

I argue similarly that if a structure has time as a fully integrated dimension, the structure is dynamic. For instance, the mental representation of a person walking is most parsimoniously modeled as a dynamic structure, not, say, as a static representation of a person operated on by some process that step by step makes the person walk (cf. Cutting & Proffitt, 1981).

Why "dynamic"? The word *dynamic* is used throughout this article. Dynamic has both a general meaning of "not static," and a more specific meaning of "relating to energy or physical force in motion." Both meanings are reflected in my use of the word; it is possible that in some cases *kinematic* or even *temporal* could have been used instead. However, both theoretical considerations and experimental results lead me to prefer the word *dynamic*. Consider a representation of objects in the environment. The necessary criterion implies not only that time become coupled with the spatial dimensions in the representation but also that time become coupled with other fundamental properties of the objects that are represented, such as mass. In the following section I will describe experiments that suggest a mental analogue to momentum; this implies a coupling of represented information about time and mass and thus dynamic representations. Although the role of perceived mass has not yet been investigated directly in the representational momentum paradigm, studies investigating the possible role of perceived forces have been initiated (Freyd & Cheng, 1986; see discussion in the Conclusions section of this article). Representing statics as forces in equilibrium certainly implies the appropriateness of dynamic. Eventually I would like to extend the notions of mass and force, and how they interact with the temporal dimension, into cases where the mental representation is not of objects in our environment but of more abstract things where mass and force might have abstract mental analogues.

Dynamic Characteristics of Mental Representations: Momentum

Finke and Freyd and their colleagues (Finke & Freyd, 1985; Finke, Freyd, & Shyi, 1986; Finke & Shyi, in press; Freyd & Finke, 1984, 1985; Freyd & Johnson, 1987; Kelly & Freyd, 1987) have recently discovered a memory distortion, referred to as *representational momentum*, that is consistent with the notion that mental representations are dynamic. Although these studies do not prove that representations are dynamic, they suggest that under some conditions a directional, continuous dimension of time seems to be necessarily represented. Some of the basic findings will be summarized, and then discussed in terms of the definitional criteria proposed for dynamic mental representations.

1. *The basic phenomenon.* Under appropriate conditions an observer's memory for the final position of an abruptly halted object is distorted in the direction of the represented motion, much as a physical object continues along its path of motion because of inertia. This phenomenon has been termed *representational momentum*. In their original study, Freyd and Finke (1984) presented subjects with a static figure at a number of orientations along a possible path of rotation (see Figure 4A), each orientation being separated temporally with an interstimulus interval (ISI) of 250 ms. They 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. There were two ways the orientation could be different: It could be a small rotation in the same direction as the implicit motion or an equally small rotation in the opposite direction. Subjects were less successful in detecting differences when the

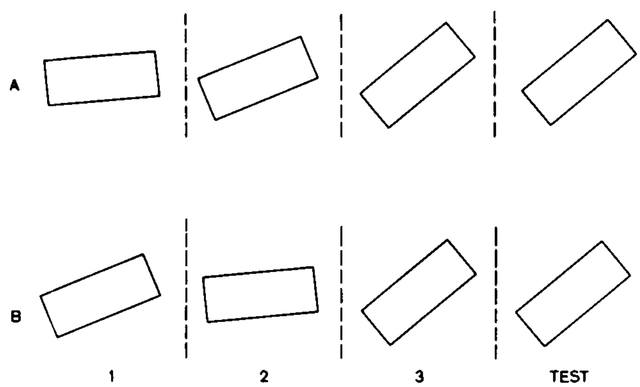

Figure 4. Examples of display sequences used by Freyd and Finke (1984). (The three stimulus presentations plus the test pattern, which were presented sequentially in the experiments, are shown here from left to right for [A] coherent motion displays and [B] displays without coherent motion. Test patterns on the far right are for the "same" trials, in which the test pattern orientation matched that of the third pattern in the sequence.)

differences were in the direction of implicit motion (see Figure 5A and 5B), suggesting that their memory for the third orientation had been distorted along that direction.

2. *The effect depends on coherent implied motion.* Freyd and Finke (1984) found no momentum effect when the ordering of the first two orientations in the inducing display was reversed so that there was no longer a consistent path of implicit motion (see Figures 4B, 5C, and 5D).

3. *The momentum effect is different from guessing the next logical position in the sequence.* Freyd and Finke (1984) and Finke and Freyd (1985) also investigated a possible alternative explanation of the early results: that subjects could not help mentally jumping from the third inspection pattern to the next logical orientation in the sequence, despite the fact that the task subjects were asked to perform discouraged them from doing so. In control experiments, distractors were used with displacements such that the "forward" distractors were physically what would have been the next stimulus in the sequence. If subjects were anticipating the next logical stimulus in the sequence they should have had great difficulty rejecting distractors in the predicted position relative to a "backward" position. In fact, however, there were no significant effects for forward versus backward distractors in this control experiment. That is, subjects were not merely anticipating that the final inspection pattern would be the next logical orientation in the sequence. Instead, the results indicate that the error in memory for position is best thought of as a small shift in the forward direction. Similarly, Finke and Shyi (in press) showed that when explicitly asked to extrapolate the motion, their subjects did not overestimate the distance the object would travel and were generally quite accurate, suggesting that subjects do not mistakenly treat the memory task as an extrapolation task.

4. *The effect does not seem to stem from sensory processes.* Finke and Freyd (1985), using implied independent translatory motion of dots, found strong momentum effects with inducing ISIs and *retention intervals* (ISI between third and fourth pattern) up to 2 s, suggesting that the momentum effect is a product of central processing and not triggered motion detectors.

5. *The effect is impervious to practice or error feedback.* Finke and Freyd (1985) reported that error feedback and practice do not serve to weaken the momentum effect. In addition, Finke and I and our associates have informally noted that the effect seems to be impervious to extensive knowledge of the predicted results and attempts to compensate for the effect.

6. *The momentum effect represents a shift in memory for position.* Freyd and Finke (1985) replicated their original experiment (1984) using a different distribution of test orientations: Nine different test orientations were presented equally often, and only one of those orientations was truly the same. Four of these nine test orientations were clockwise rotations from the third orientation, and four were counterclockwise rotations. Every subject Freyd and Finke (1985) tested produced 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 (see Figure 6A).

7. *The memory shift increases with display velocity.* There is also evidence that the magnitude of that memory shift is a linear function of the implicit velocity of the inducing display (Freyd & Finke, 1985). This was predicted from the momentum metaphor, as physical momentum is proportional to velocity. Quadratic regression curves were fit to the data for each of several implied velocities, and the peaks of the curves were then evaluated. The peaks are considered to be estimates of the amount of memory shift. Freyd and Finke (1985) reported a correlation of .9 for degree of memory shift and the implied velocity of the inducing display (see Figure 6B). Finke, Freyd, and Shyi (1986) then showed that observers are sensitive to the implied *final* velocity and not simply the average velocity.

8. *Representational momentum occurs very rapidly.* Memory distortions can be observed when extremely short retention intervals (10 to 100 ms; see Figure 7) are used between the to-be-remembered and test displays (Freyd & Johnson, 1987). This suggests that the mental mechanisms underlying the effect are very rapid.

9. *The shift increases over short retention intervals.* Freyd and Johnson (1987) found that memory shifts increase with retention interval for small intervals (see Figure 7). Also, for very short retention intervals the memory shifts are slightly less than the product of retention interval and the implied velocity of the inducing display, as predicted from the analogy to physical momentum.

10. *The momentum is attached to the represented object, not an abstract frame of reference.* Kelly and Freyd (1987) showed that the momentum effect depends on perceived object identity over the successive static presentations in the inducing display. Minor fluctuations in object identity such as internal texture changes or small shape changes weaken the momentum effect; major fluctuations in object identity such as radical shape changes lead to no momentum effect at all.

11. *Representational momentum exists for dimensions of change other than those involving rigid visual transformations.* Kelly and Freyd (1987) found momentum effects for implied deforming transformations such as object shape (a rectangle getting fatter or thinner) as well as for a nonvisual implied transformation (changes in pitch).

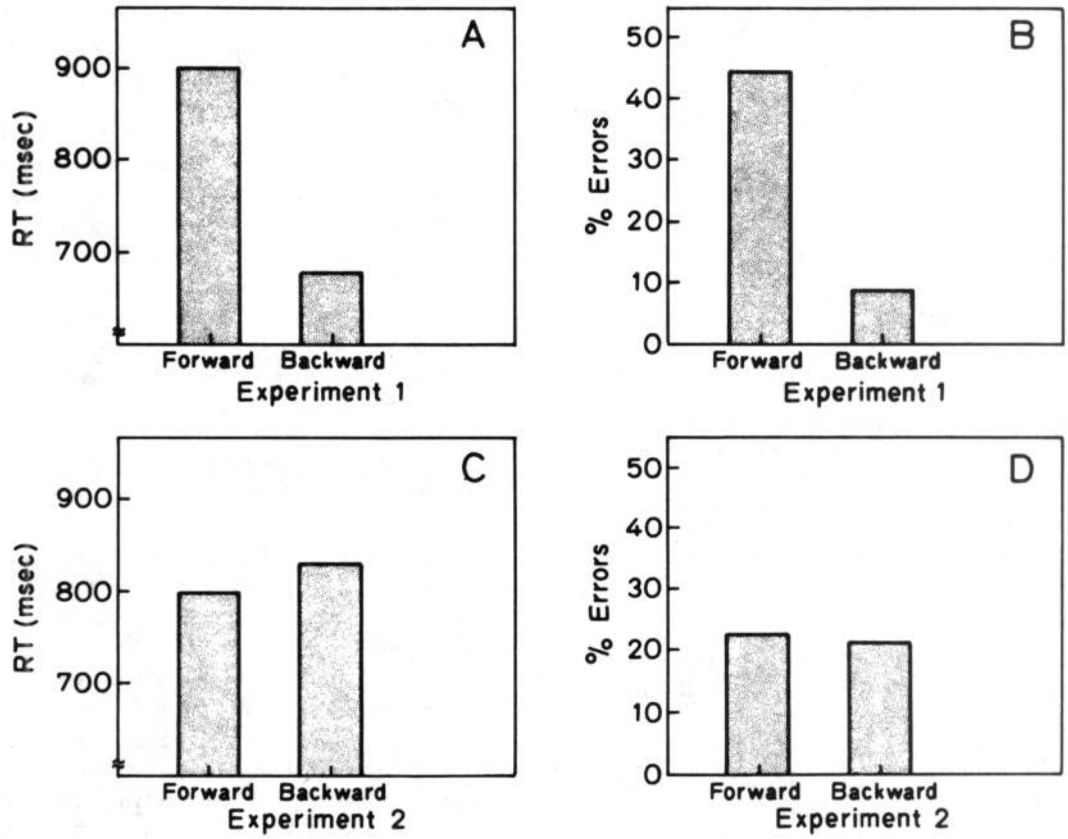

Figure 5. Mean reaction times (in milliseconds) and error rates for forward and backward conditions used by Freyd and Finke (1984); Panels A and B show results for displays using coherent motion; Panels C and D show results for displays without coherent motion.

Implications of Momentum Results

The representational momentum phenomenon (Finding 1) depends on coherent dynamic information (Finding 2) and is not dependent on peripheral perceptual processing (Finding 4); it thus speaks to issues of dynamic information and mental representation.

That subjects cannot remember the position of the object without being biased by the implied dynamics of the object (e.g., Findings 1 and 6) and that those effects are impervious to practice or error feedback (Finding 5) support the necessity criterion for dynamic mental representations. Necessity is further supported by the finding that the momentum is attached to the mental representation of the object, not some general abstract frame of reference (Finding 10). The directionality criterion is supported by the finding that the internal transformations follow the direction of the implied motion of the inducing display (Finding 1) if that motion is coherent (Finding 2).

Most important, the motion information appears to be represented continuously because when probed at a variety of early retention intervals the memory shift was found to increase lawfully with the retention interval (Finding 9). That is, the memory shift was found to correspond to intermediate positions along the rotational continuum. This finding is analogous to Cooper's (1976) demonstration that in mentally rotating a figure, orientations between the initial and final points of the rotation are represented. An important difference between the evidence suggesting continuity for representational momentum and that for mental rotation, however, is the much greater resolution in measuring mental transformations in the case of representational momentum. The relation between memory shift and retention interval (Finding 9) is for fractions of a degree of rotation and hundredths of a second; as opposed to the 15- or 30-degree increments and large fractions of a second that Cooper (1976) reported.

The momentum effect may differ from the mental rotation finding in another important way: Representational momentum, as compared with mental rotation, is more clearly characterized as *cognitively impenetrable* (see Fodor, 1983). Pylyshyn (1981) has argued that mental rotation can be affected by beliefs and task expectations and therefore is not intrinsically an analogue process but, instead, results from an abstract symbol system that includes beliefs about "natural" transformations. In contrast, representational momentum is not likely dependent on task demands as subjects are asked to remember a static position and to refrain from transforming anything. In addition, as Kelly and Freyd (1987) have argued, representational momentum appears to be "informationally encapsulated" (see Fodor, 1983) given that it is very rapid (Finding 8) and mandatory (Finding 5) and thus not subject to influence by beliefs. Thus the evidence indicating that the momentum effect results from

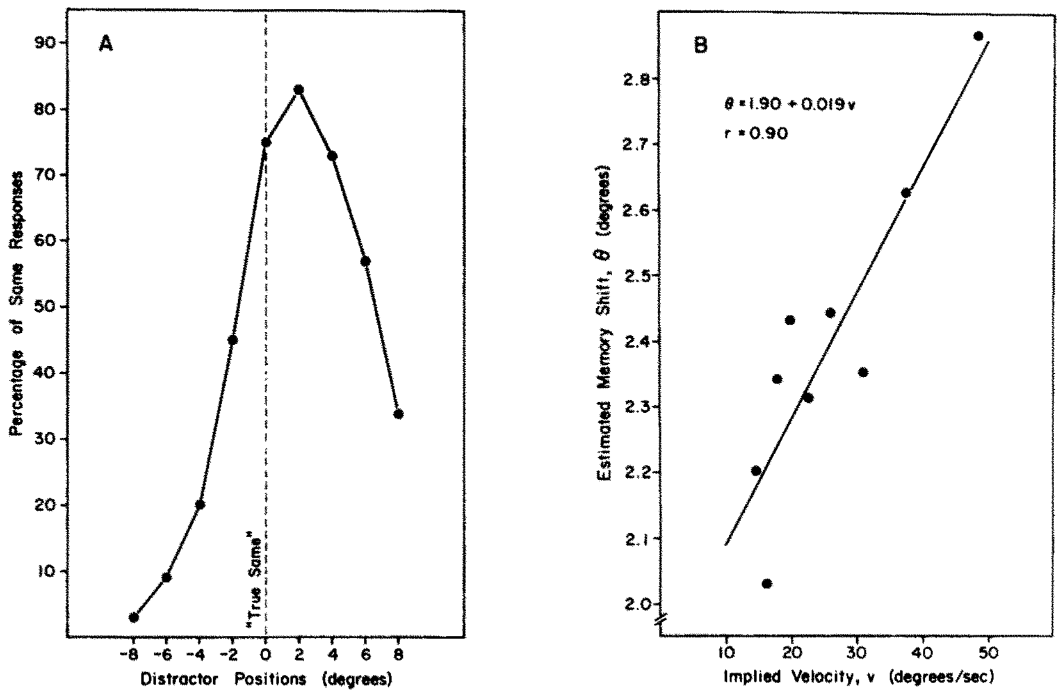

Figure 6. Results from Freyd and Finke (1985): (A) averaged across all subjects and conditions (positive values represent "forward" displacements of the fourth rectangle; negative values represent "backward" displacements); (B) shift estimates derived from quadratic regressions are plotted against implied velocity.

a continuous mental transformation (Finding 9) may be the strongest support in favor of analogue representations currently available, as well as supporting the continuity criterion for dynamic mental representations.

The results indicating that representational momentum has properties analogous to physical momentum (Findings 8 and 9) may provide additional support to dynamic mental representations because time is clearly necessary for physical momentum. Alternatively put, physical momentum is a property of objects embedded in a spatiotemporal world; representational momentum may likewise be a property of mental representations with spatiotemporal coherence. This argument points to the similarity between mental and physical momentum as evidence of similarity in the underlying structures in the mind and in the world, not as evidence of an adaptive internalization of physical rules (see Kelly & Freyd, 1987, for a discussion of the possible adaptiveness of representational momentum).

Finally, representational momentum also appears to be a general phenomenon, not limited to implied rigid transformations, nor even visual transformations (Finding 11). This finding suggests that the momentum metaphor should be interpreted abstractly, not literally. Again, it is the underlying similarity in structure between time and momentum in the world and time and momentum in the mind that I am concerned with here. Thus I would expect to find representational momentum for any dimension of continuous change, but not discontinuous change, (cf. Findings 3 and 9) that can be mentally represented.

Concluding Remarks on the Special Status of Dynamic Information

In this last section of the article, I will speculate on three issues related to the special status of dynamic information: the mental representation of action, the possibility that statics may be perceived as forces in equilibrium, and ways that movement may be captured in art.

Mental Conceptions of Actions

I would like to allow for the possibility that nonimagistic sorts of mental representations can be dynamic. Although the temporal dimension would have to be an intrinsic representation of time, and it would have to be necessary, the other dimensions or relations represented could conceivably be nonimagistic, even propositional. However, if one assumes that mental representations are dynamic, certain arguments in favor of abstract coding over imaginal coding must be reconsidered. One point that is often made is that an analogical code cannot represent certain concepts. Premack (1983), for instance, argued that concepts of relations, such as opening, can only be represented in an abstract code because there is no way of having an image of the relation in general, such as opening per se. Yet, no single static image can look exactly like every member of a category even if the category is based on the static appearance of its items (such as the category *animal*). What, then, is fundamentally different about the representation of an action or relation? Why not imagine a generic case of *opening* (see also Freyd, 1983b) as well as a generic case of *animal?* There are many similar examples of concepts that are inherently dynamic. For instance, concepts such as causality, or even justice, involve time. Whether the mental code used to represent such concepts is abstract or analogical, a representation that naturally includes time would be much simpler than one that does not.

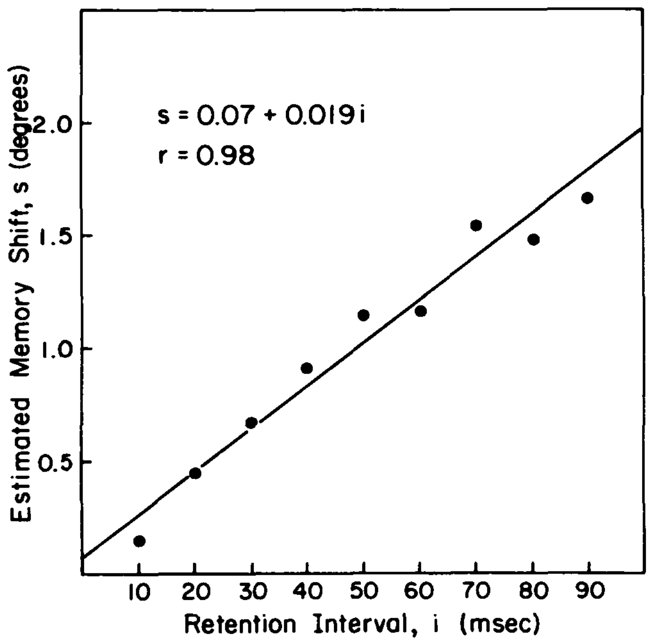

Figure 7. Results from an experiment reported by Freyd and Johnson (1987). (Shift estimates derived from quadratic regressions are plotted against retention-interval condition.)

Perceiving Statics as Forces in Equilibrium

One could argue that there really are very few situations in which an idea or concept is totally static. For example, although the concept of an object (such as *coffee cup*) seems more static than the concept of an action (such as *drinking coffee*), it may be, as suggested by Cassirer (1944), Helmholtz (1894/1971), Shepard (1981), and others (see Hochberg, 1979, 1981, for a discussion), that the perception of all objects depends on knowledge of their possible transformations. As Helmholtz wrote, "Being acquainted with the material form of an object, we are able to represent clearly in our minds all the perspective images we expect to see when we look at it from different sides . . ." (1894/1971, p. 504).

If mental representations are most naturally dynamic, one might want to say that static representations, if they exist, are special cases of dynamic representations. This suggests an interesting parallel to the development of physical theory: Not until Galileo did physicists realize that the world is best conceptualized as having naturally moving parts, that static objects are usually static because of counterbalanced forces being applied to them (such as gravity and the normal force of the earth), and that moving objects stop because of the force of friction. That is, in the modern view of basic physics, virtually all objects in our environment fail to move only because supporting forces are balanced against gravitational forces or the like, and even so, objects are conceived according to their possible motions. For example, we regard a resting object as having a potential energy, which is converted to kinetic energy when the motion takes place. Similarly, the mind might represent nonevents (e.g., objects) according to the ways in which they could be part of an event (e.g., moving objects). Recent research (Freyd & Cheng, 1986) supports just such a claim. We showed subjects pictures of two objects at rest, one supporting the other (e.g., a lock hanging from a hook or a lock sitting on a block). This was followed by a picture of the previously supported object (e.g., the lock) shown alone but in the same position. Subjects were asked to remember the object's position. In the critical trials subjects were then shown the previously supported object alone and in a slightly different position. They were asked to indicate whether the position of the object had changed. If the new position was in the direction of change that the object would have moved in real life with the removal of support, subjects were very likely to incorrectly respond "same." This finding supports the claim that even the perception of objects at rest involves the mental representation of dynamic information.

Art and Movement

People often comment that a particularly pleasing painting, photograph, or sculpture captures some sort of movement (e.g., see Arnheim, 1972). As the survey by Friedman and Stevenson (1980) and the results of the experiments on picture perception (Freyd, 1983c) suggest, this aesthetic may be due to the nature of the mental representations of such art. Thus, when viewing Michelangelo's *David*, one of the reasons for excitement might be that the mental representation of the sculpture is particularly dynamic; that we anticipate the potential movements of the static form. Another way in which art might be dynamic is by virtue of the balance of opposing forces; Arnheim (1972) suggested that visual dynamics are particularly strong when the picture is in a kind of equilibrium (perhaps as in the displays used by Freyd & Cheng, 1986).

There is yet another possible source of movement information in art, analogous to the tacit knowledge of handwriting methods (Babcock & Freyd, in press; Freyd, 1983d): Some works seem to come alive through the dynamics underlying their physical construction. For instance, it seems that knowing the technique used to produce a painting can often make the painting come to life and be appreciable as art. (This is different from respecting good technique as such.) Knowing that Jackson Pollock rehearsed each painting, that his finished product is the record of highly controlled sweeps of his arm, can drastically change (and perhaps improve) the perception of his paintings. Likewise, the Japanese are conscious of the fact that a master calligrapher creates his work in moments, after years of rehearsal, and that the motion totally determines the final form; thus the motion is what is often discussed by critics.

Summary

Earlier in this article I argued that the importance of perceiving dynamic information, which has been recognized by many students of motion and event perception, extends to the perception of stimuli that are not changing in real time. I went on to argue that dynamic information may be crucial to mental representation as well. One connection between these arguments involves speculation about the evolution of the mind: Higher cognitive mechanisms are often thought to have their evolutionary root in the perceptual system (Shepard, 1981; Shepard & Podgorny, 1978; see also Fodor, 1972; Rozin, 1976), and to the extent that dynamic information is important to perception, we may expect it to be important to representation.

Thus the same basic dynamic representation might be used for the perception, the memory, and the imagination of certain events (such as a person walking). Similarly, to the extent that the perception of even a static object depends on a representation of forces held in equilibrium, dynamic representations from higher cognitive processing may be used in perception. Thus, even when something is not an event, such as a coffee cup, it might be normally represented as if it could be part of an event, such as a coffee cup falling or being picked up.

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Cutting Appointed Editor of the *Journal of Experimental Psychology: Human Perception and Performance,* 1989–1994

The Publications and Communications Board of the American Psychological Association announces the appointment of James E. Cutting, Cornell University, as editor of the *Journal of Experimental Psychology: Human Perception and Performance* for a 6-year term beginning in 1989. The current editor, William Epstein, will be receiving submissions through September 30, 1987. At that point, the 1988 volume will have been filled, and all submissions after that should be sent to James Cutting. Therefore, as of October 1, 1987, manuscripts should be directed to:

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