Anticipatory spatial representation of natural scenes: Momentum without movement?

Helene Intraub

University of Delaware, Newark, USA

Does mental representation of the immediate past contain anticipatory projections of the future? In cases of representational momentum (RM), the last remembered location of a moving object is displaced farther along its path of motion. In boundary extension (BE), the remembered view of a scene expands to include a region just outside the boundaries of the original view. Both are "errors", yet they make remarkably good predictions about the real world. The factors affecting these phenomena, the boundary conditions for their occurrence, and their generality to non-visual senses (audition or haptics) are reviewed to determine if RM and BE are fundamentally related. In contrast to Hubbard's (1995b) suggestion that they may share a common underlying mechanism, it is proposed instead that RM and BE are related in a more general sense and may be different instantiations of the dynamic nature of mental representation.

A powerful means of exploring the nature of mental representation is to study the errors that perceivers share in common; representational momentum (RM) and boundary extension (BE) are two such errors and provide opportunities for understanding the mental representation of events that unfold over time. What is particularly interesting about these phenomena is that although in one sense they are errors (i.e., they differ from the physical stimulus), in another sense they provide remarkably accurate predictions about characteristics of the world that have not *yet* been perceived.

In the case of RM, when a moving object vanishes, within moments, observers misreport its last seen position as being farther along the path of motion than it actually was (Finke & Freyd, 1985; Freyd & Finke, 1984). In the case of BE,

when a photograph is presented and removed, observers misremember the limits of the view—they remember having seen more of the scene, as if the photograph's boundaries were displaced outward. In our experience with the world, moving objects do continue along their trajectory unless something stops them; and when we view a scene, within in a fraction of a second a saccade or head movement will indeed expose the adjacent (previously unseen) region of the environment. The purpose of this paper is to explore the question of whether these two phenomena bear only superficial similarity, or if they are more fundamentally related.

When boundary extension was first reported, Intraub and Richardson (1989) noted the general similarity between BE and RM. At that point in time, however, certainly not enough was known about BE to shed any light on a possible connection. More recent research on both phenomena now provides an opportunity to examine their similarities and differences. If their connection is more than a nominal one, there are two theoretically significant ways in which they might be related. They might draw upon common (or very similar) underlying mechanisms (Hubbard, 1995b, 1996), or they might draw upon different specific mechanisms, but reflect the dynamic nature of mental representation and serve a similar purpose in cognition.

DYNAMIC REPRESENTATION OF SCENES

The inducing stimuli in much of the research on RM are animated sequences or implied motion sequences (i.e., successive views of a movement that do not support apparent motion) of simple objects against blank backgrounds: for example, moving dot patterns (Finke & Freyd, 1985), and geometric forms undergoing rotation, translation, or size change (Freyd & Johnson, 1987; Hubbard & Bharucha, 1988; see Hubbard, 1995b, for a review). Inducing stimuli in the case of BE are photographs or drawings of scenes that depict a single view (i.e., a "still life"). Whereas RM is related to characteristics of movement (e.g., velocity, acceleration), BE appears to be related to characteristics of space—in particular, the continuity of spatial layout in scenes (Intraub, Gottesman, & Bills, 1998; Gottesman & Intraub, in press). Given this categorical difference, it would seem wise to begin a comparison by considering research on the same stimulus type. BE is specifically related the scene perception. Does RM occur in the context of natural scenes?

The RM literature to date does not appear to include cases in which objects move within a natural scene context, however, research on the effects of frozen motion in still photographs of scenes (see Figure 1 for an example) has shown an effect very similar to RM; in fact, one such study (Freyd, 1983) was a precursor to the discovery of RM. Freyd (1993) has argued convincingly that the impact of frozen action photographs and actual motion on mental representation is derived from the same principles.

Figure 1. Example of a "frozen motion" photograph, similar in kind to those used in Freyd (1983) and Futterweit and Beilin (1994).

Implied motion in static scenes (frozen action)

In the first such study, Freyd (1983) presented pairs of frozen action photographs taken from a single movement (e.g., a person jumping off a wall). The pair was presented either in real-world temporal order or in reverse (in filler trials, the same picture was presented twice). The first picture was presented for a duration of 250 ms followed by a 250 ms retention interval and then the second picture. The second picture remained on the screen until the viewer indicated if it was the "same" or "different" via a key press. An asymmetry in response time was obtained suggesting that it was more difficult to reject a distractor that was farther along the implied path of motion than the reverse: it took, on average, 59 ms longer to do so. However, although there was a similar asymmetrical trend in response accuracy, unlike typical RM results, correct rejection of the distractors did not differ between conditions.

Futterweit and Beilin (1994) attempted to address the accuracy issue by replicating Freyd's (1983) study using a more sensitive test. They also tested the effect both in children (8–10 years of age) and adults to determine if the phenomenon was age related. They adapted a test method first used by Finke and Freyd (1985) in RM research in which potential distractors included several earlier and later positions in the action sequence. In several RM studies that used this test method with either dot patterns or simple forms undergoing change across an inducing sequence (e.g., Finke, Freyd, & Shyi, 1986; Freyd & Finke, 1985; Kelly & Freyd, 1987) the greatest percentage of "same" responses, was not to "true same", but to the display showing a slight displacement in the path of motion (+1 position). In Futterweit and Beilin's adaptation, the second frozen-action photograph in the sequence was either the same picture, one of three preceding views or one of three following views from a filmed sequence of the action. In this case, both children and adults showed RM-like accuracy errors in their responses to the distractors. They were more likely to accept the +1 test picture than the –1 test picture, and did so frequently. Unlike RM research with simpler stimuli, Futterweit and Beilin found that the highest frequency of "same" responses was to "true same".

Freyd, Pantzer, and Cheng (1988) also demonstrated an effect on accuracy of implied motion in static scenes. In this case, they showed pairs of line-drawn scenes in which an object was always in the same position, but was either supported (e.g., flowerpot on table, flowerpot supported by ceiling hook), or not supported (e.g., table or hook deleted). When the "support present" scene preceded the "support absent" scene, the object was remembered as having been lower in the picture space than it actually was. Viewers were more likely to accept a distractor showing the object slightly lower in the picture space than the reverse. It was as if the mental representation of the scene included not only information that was physically present in the picture, but dynamic expectations about the likely downward motion of an object that is suddenly without

support. Again, the highest number of same responses was to "true same" suggesting the effect was more moderate than in RM studies.

A dynamic effect of implied motion in static scenes is clearly evident in these studies. However, the effect does not appear to be as strong as in RM studies in which an inducing sequence is used that implies continuous motion by showing a stimulus in successive positions that are consistent with real movement. Whether this is because the static pictures of scenes: (1) lacked the saliency of real motion, (2) were tested with less sensitive distractors, or (3) provided so much background detail that the viewer could more easily localize the target during the test, is not clear. In related research on the ability to detect displacements in the position of point-light walkers across saccades, Verfaillie (1997) has shown that placing landmarks (i.e., companion walkers) in the display improved viewers' ability to recognize a horizontal displacement of the target walker. However, these landmarks only yielded marked improvement when they caused the formation of a perceptual group (an organized configuration). Given the organizational properties of natural scenes, it might be worthwhile to test the effects of RM with inducing stimuli that contain natural backgrounds. However, this does not diminish the fact that frozen motion in static scenes does indeed yield a dynamic representation.

Implied continuity of layout in scenes: Boundary extension

In the case of boundary extension, photographs of scenes with no implied motion also yield dynamic representations—but the mental extrapolation takes a different form. Although the stimuli are best described as "still-life" views, the ensuing mental representation includes dynamic projections about the surrounding layout—a surrounding region that was not shown in the picture, but is likely to have existed in the world, just beyond the edges of the view (Intraub & Richardson, 1989). Both drawing tasks and recognition tests have shown the same unidirectional error in the representation of a static view of a scene (Intraub & Berkowits, 1996; Intraub & Bodamer, 1993; Intraub & Richardson, 1989; Legault & Standing, 1992; Nyström, 1993). An example (from two different experiments) of two photographs that provide close-up views of scenes (top panels), a representative subject's drawing of each close-up from memory (middle panel), and two photographs that provide a more wide-angle view of each scene are shown in Figure 2.

As may be seen in the figure, the drawings depict a more wide-angle view than was shown in the close-up photographs the subjects had tried to remember. A comparison of their drawings to more wide-angle photographs of the same scenes shows that the extrapolated regions actually predicted the surrounding space quite well. This effect is very robust and appears to be the rule rather than
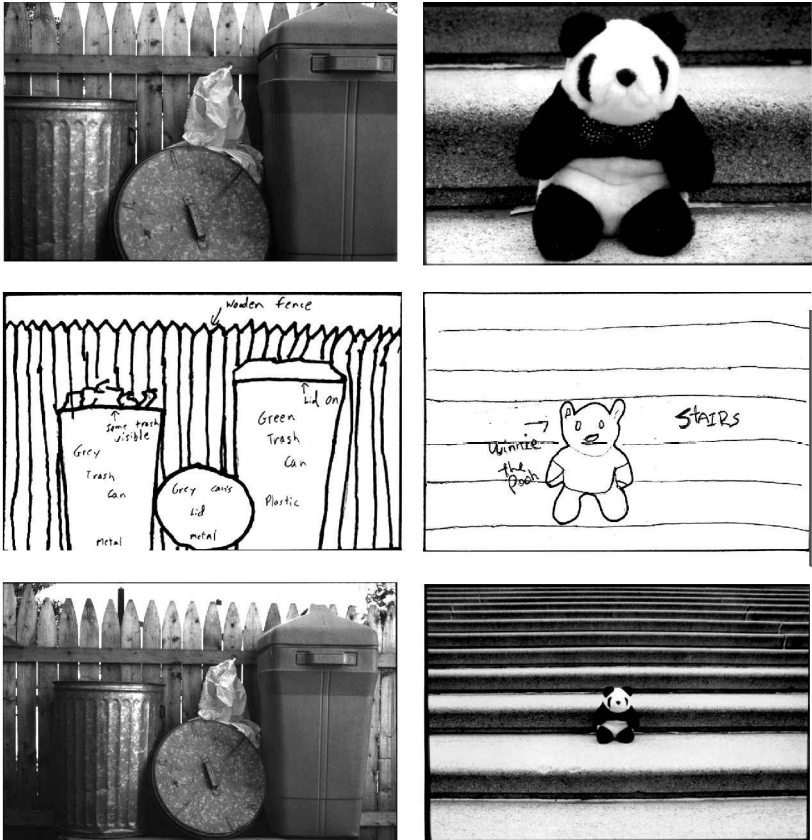
Figure 2.   The left column shows a close-up view of "trash cans by a fence", a subject's drawing of the close-up from memory 48 hours later, and a more wide-angle view of the same scene (based on Intraub & Richardson, 1989, Fig. 1). The right column shows a close-up view of a "toy bear on the steps", a subject's drawing of the close-up from memory minutes later, and a more wide-angle view of the same scene (based on Intraub, Gottesman, Willey, & Zuk, 1996, Fig. 1). Note that the subjects' drawings contain an extrapolated region around the perimeter of the scene that was not present in the close-up, but was clearly present in the scene (as shown in the wide-angle view). The photographs were presented in colour, and the original pencil drawings were traced in black ink for reproduction.

the exception (e.g., Intraub & Berkowits, 1996; Intraub & Bodamer, 1993; Intraub et al., 1996; Intraub & Richardson, 1989; Legault & Standing, 1992). For example, Intraub and Richardson (1989) reported that 95% of 133 pictures drawn by 37 undergraduates showed boundary extension after a 35 minute interval. The same has occurred for much smaller set size and brief intervals (e.g., Intraub & Berkowits, 1996: Intraub et al., 1996). Most recently, Seamon, Schlegel, Hesiter, Landau, and Blumenthal (in press), reported sizeable

degrees of extension in drawings made by children (6–7, and 10–12 years of age), young adults (18–21 years), and older adults (58–84 years), who drew each of four photographs immediately following its offset.

In most BE research, however, spatial representation is tested by first presenting a series of scenes, and then presenting a test in which each item either shows the same view of a stimulus scene or a more close-up or more wide-angle view. As in the case of frozen motion (and RM) studies, one cannot know, a priori, that a distractor will show the right amount of change to match the hypothesized mental extrapolation. In BE, we have addressed this problem by using a rating scale rather than a binary same/different choice in our tests. Subjects rate targets and distractors on a 5-point scale to indicate if the test picture is the same view, or shows more (slightly more, or much more) or less (slightly less or much less) of the view.

As in the case of RM and frozen motion photographs, responses tend to be asymmetrical. Viewers are more likely to rate the identical views as being "too close up" rather than "too wide-angle". For example, in Intraub and Richardson (1989: Expt. 2, recognition only condition) subjects rejected the identical close-ups as "true same", 50% of the time, rating them as being "too close up"; rarely, if ever, did they rate the test picture as being "too wide-angle" (only 0.02% of the trials). When an identical view appears to be "too close up" (i.e., truncated), this indicates that viewers' mental representation of the original includes extrapolated space (also shown in Intraub, Bender, & Mangels, 1992; Intraub & Bodamer, 1993; Intraub et al., 1996, 1998). Ratings to distractors also tend to be asymmetrical, indicating that the stimulus was remembered with extended boundaries. For example, when pairs of close-up and wider-angle views of a scene are presented in different orders so that one is the stimulus and the other is the test item (somewhat analogous to Freyd's, 1983 test), their rated similarity differs depending on which order is used (Intraub et al., 1998; Intraub & Richardson, 1989). If the closer view serves as the stimulus and the wider-angle view serves as the test item, viewers rate them as being somewhat similar. If the wider-view is presented first, viewers rate them as being very different.

Other types of tests have yielded similar results. In an interactive test (Gottesman & Intraub, 2001), subjects viewed each of four computer-printed photographs (each contained two central objects) and then reconstructed the scenes by placing cut-outs of the objects on a printed photograph of the background alone (homogeneous natural backgrounds such as carpeting were used). They chose from among five different-sized cut-outs of each object: One was the same size as the object in the original picture; the others were either expanded or reduced in size (length and height were increased or reduced by 8% using a graphics program prior to printing the objects). A large BE effect was obtained. Overall, subjects selected smaller-sized versions of the objects more than twice as often as they selected "true same". They obtained a similar

pattern of results in a 5-alternative forced choice test with full scenes. In another interactive test, Nyström (1993) showed subjects a photograph and then presented a larger photograph that included the original information in addition to showing more of the surrounding space. Subjects had to mark the boundaries of the original picture using sticks. Again BE was obtained.

Effect of picture view

BE is strongest for very tight close-ups and decreases as the picture view widens. Because the first report of BE used close-ups (the "wide-angle" views were only relatively wide-angle) and long retention intervals (35 min or 2 days), it was possible that BE reflected a long-term memory distortion in which very close (and very wide) views regress toward a prototypic (standard) view. This could account for BE in Intraub and Richardson's (1989) experiments. However, this hypothesis would predict an equal and opposite effect (i.e., boundary restriction) if very wide-angle views were presented. To test this, based on normative ratings, Intraub et al. (1992) selected three views of the same eighteen scenes that were rated as very close-up, close prototypic, or as very wide-angle and presented them to other groups of subjects in a series of experiments.

When the recognition test immediately followed presentation, close-ups yielded the greatest amount of extension, followed by prototypic views (which also yielded extension). The very wide-angle views (e.g., see the wide-angle view of the "bear" in Figure 2) yielded either a little BE or no directional distortion—they did not yield boundary restriction. This pattern has been replicated in several other studies using both recognition and drawing tests (Intraub & Berkowits, 1996; Intraub et al., 1992, 1996, 1998). Clearly the prototypic view hypothesis was not supported.

Intraub and her colleagues proposed that BE reflects perceptual processes activated during scene perception that allow the viewer to understand a partial view of a continuous world by perceiving (amodally, not visually) that the view continues. This is incorporated in the viewers' mental representation of the picture. They argued that a close-up view of a scene (with a central object) imparts a great sense of expectancy. The continuity of the surroundings just outside the view is highly predictable (as can be seen in the accuracy of subjects' extrapolations in Figure 2). As the view widens, the expected region surrounding the attended object becomes increasing available within the picture. As the boundaries become more peripheral to the attended object, consistent anticipatory projection outward no longer occurs. After a long retention interval, however, something different happened, that also seems to occur in the case of RM.

TIME COURSE OF RM AND BE

Two-component models of RM and BE

Intraub et al. (1992) found that after a 2-day delay, the degree of BE obtained was less pronounced than when viewers were tested immediately following presentation. Was memory becoming more veridical over time? An analysis of the degree of boundary extension for the same subset of pictures when they were among the closest views in the set versus when they were among the most wide angle views, showed that this was not the case. The reason for less BE over time was that another process was having a countervailing effect. Over time, the views normalized toward the average of the set (i.e., regression to the mean). In other words, objects covering a large portion of the picture space (in close-ups) were remembered as smaller (more wide-angle), and those covering a small area (in wider-angle views) were remembered as larger (more close-up). We referred to this interactive process as extension-normalization. Perception of the photographs causes boundary extension, but then over time, normalization in memory diminishes the effect.

Freyd and Johnson (1987) observed a similar pattern when RM was tested over various time intervals. The inducing stimulus was a sequence of successively presented rectangles, each of which was tilted 17° ahead of the previous one. The test item was presented following retention intervals ranging from 10 ms to 90 ms. The amount of displacement in the direction of the motion (for the *same* inducing sequence) increased monotonically with increases in the retention interval. That is, the remembered location of the final rectangle depended on when in time that representation was probed—the representation is dynamic. Increases like this have been observed up to about 200 ms (Freyd, 1993). However, the effect peaked at about that time and then either diminished or reversed as the retention interval increased further (e.g., Freyd & Johnson, 1987; also see Hubbard, 1995b, 1996). Freyd and Johnson (1987) proposed that two different processes were responsible for this pattern. The early process is due to the effects of representational momentum, and then over time, memory averaging occurs and causes the representation to shift back to the mean of the set. This appears to be the same dynamic interaction reported in Intraub et al.'s (1992) extension-normalization model, although over a much briefer period of time than in the case of boundary extension. First there is a dynamic anticipatory shift, and then later memory averaging serves as a countervailing influence on the representation.

Finally, other than normalization (averaging) effects, other factors can moderate both BE and RM. For example, in research pitting "tunnel vision" against BE, Safer, Christianson, Autry, and Osterlund (1998) showed that in a picture in which the central character is undergoing a traumatic experience, BE will be less expansive than if the central character is undergoing a neutral experience in a scene that is otherwise the same. This intriguing research unfortunately used a

very small stimulus set, but raises the issue of the effects of attention and emotion on spatial extrapolation. In the case of RM, expectations about whether a target will bounce or not (Hubbard & Bharucha, 1988) and verbal biases about whether it will "bounce" or "crash" (Hubbard, 1994), have been shown to influence the course or magnitude of representational momentum.

Testing the representation after brief intervals

Unlike RM experiments, most studies of boundary extension have tested memory following relatively long stimulus durations (e.g., 15 s) and relatively long retention intervals (a few minutes to 2 days in length). This provided the observer with plenty of time to study the picture, and showed that BE would persist over a wide range of intervals (Intraub et al., 1992; Intraub & Richardson, 1989). Does BE occur immediately after presentation under timing conditions closer to those observed in RM?

Intraub et al. (1996) used temporal parameters that would be in the range of a single eye fixation or a series of eye fixations. The first goal was to determine if BE would occur following the first fixation on a scene, and the second goal was to determine if BE would occur as soon as 1 s following picture offset. It was thought that BE would occur following a single fixation if that brief interval provided enough information about the scene's layout. If the first glimpse only delivers the basic meaning (i.e., "gist") of the scene and some detail, then because viewers fixate centrally, memory for the periphery of the view might be very poor, resulting in random errors in recall of border placement rather than the consistent unidirectional extrapolation of layout seen after longer durations.

Seven pictures were presented for either 4 s or 250 ms each, at an SOA of 5 s with a visual noise mask between presentations. Scene representation was tested using both recall (see Figure 2, right column) and recognition procedures. BE occurred after both durations, in both types of tests. Not only did BE occur following a brief glimpse of a scene, but if anything the briefer duration yielded a larger amount of extrapolation. Given only a single fixation, predictive extrapolation of scene structure was incorporated in the representation. But how soon after presentation did BE occur?

In a second experiment, they presented triads of unrelated photographs at a rate of three pictures per second (a rate that mimics the rapid fixation frequency of the eye). This was followed by a 1 s masked interval and a repetition of one of the three pictures that remained on the screen for 10 s. During this time, using a 5-point scale, subjects indicated if in comparison with its first appearance, the test picture was: a lot more close-up, a little more close-up, exactly the same, a little more wide-angle, or a lot more wide-angle than it was before. Irrespective of serial position, subjects tended to rate the same pictures as being "more close-up" than before, thus indicating that their mental representation

contained extended boundaries at least as soon as 1 s following picture offset (also see Intraub, 1999). BE occurred on 59% of the 42 trials. Unlike RM, however, the effect is relatively long lasting.

COGNITIVE PENETRABILITY

Do the errors under discussion reflect fundamental properties about mental representation (i.e., automatic, low-level), or do they reflect conceptual influences (i.e., expectations, beliefs, responses to demand characteristics) that would suggest "cognitive penetrability" (Pylyshyn, 1981, 1984)?

Representational momentum

Questions were raised as to whether all aspects of RM are subject to cognitive penetrability because as described earlier, it can be affected by expectations and beliefs (Hubbard & Bharucha, 1988; Ranney, 1989). Finke and Freyd's (1989) position is that RM probably draws upon both low-level and high-level processes, so that aspects of the effect may be subject to cognitive penetrability. However, these high-level processes cannot account for its occurrence. They argue that the rapid, spontaneous instantiation of the phenomenon and the constant rate of the memory shifts in response to velocity (e.g., Freyd & Johnson, 1987) are unlikely to be the result of post-perceptual calculation on the part of the subjects. They argue further that the memory shifts seen in RM appear to be quite robust when tested after brief intervals, despite feedback and practice.

Arguments regarding possible demand characteristics were refuted by pointing out that the "demand" in these studies was to remember the specified display accurately—i.e., one needs to be accurate in order to be correct. This is in contrast to experiments in which the instruction arguably makes it correct to "act as though" (e.g., imagery scanning studies in which reaction time was the dependent measure and subjects were asked to mentally scan their images: see Kosslyn, 1995). Finally, they point to the fact that there are examples of RM effects that do not conform to our beliefs about the world (e.g., Halpern & Kelly's, 1993 asymmetrical left–right effect; and the failure to find effects of mass; see Hubbard, 1995b).

To express how both cognitive penetrability and automatic low-level processing can co-exist in RM and related phenomena, Finke and Freyd (1989) provide an excellent physical analogy:

> ... imagine a train running along a track. Once could easily change the direction of the train by switching the track ahead of it; this would be a penetrable aspect of the train's motion. However, the train would still carry its momentum along the chosen track, whichever one that might be.
>
> (Finke & Freyd, 1989, p. 407)

Although high-level factors can influence the direction of the effect, the basic phenomenon (the mental momentum) appears to reflect fundamental characteristics of mental representation.

Boundary extension

If BE is cognitively penetrable, then warning viewers in advance should prevent the error from occurring. Intraub and Bodamer (1993) tested this possibility. They did this is two ways. In one condition they described the recognition and drawing tests in advance, so that viewers would know the borders of the pictures were important to study. In the other, subjects participated in a demonstration of BE, and their error was pointed out to them. They were challenged to prevent it from happening in the experiment. The control subjects received no forewarning about the nature of the memory test or the phenomenon. All subjects were instructed to remember the objects, the background and the layout of 12 photographs they would view for 15 s each. In spite of warnings and prior experience with the effect, boundary extension occurred in all three conditions (both in a recognition test and in drawings). At best, prior knowledge and experience sometimes attenuated the size of the effect, but it never served to eliminate it.

Similarly, when subjects participated in 42 individual test trials (a situation in which subjects had repeated experience with the boundary rating test) boundary extension was not eliminated (Intraub et al., 1996). Boundary extension remains strong even when viewers draw each picture in a four-item series immediately after viewing each one (Seamon et al., in press). Inverted photographs (that were expected to force more effortful and deliberate scanning) resulted in little or no reduction in BE as compared with upright pictures (Intraub & Berkowits, 1996). And finally, to determine if expertise with spatial layout would override BE, in a pilot study we tested 60 graphics artists at the University of Delaware. Although their drawings were more aesthetically pleasing than most subjects', to their surprise they too extended the picture's boundaries.

Similar to RM, the demand characteristic in BE is for accuracy in the representation. The lack of any movement (real or implied) provides no information to subjects that they would be expected to make this error of extrapolation in drawings and recognition tests. There is considerable evidence to suggest that both phenomena have automatic low-level components that reflect the dynamic nature of mental representation.

THEORETICAL PERSPECTIVES

Representational momentum and boundary extension show the extent to which anticipatory extrapolation occurs in the mental representation of events that

observers explicitly try to remember. Both show what is arguably an automatic extrapolation beyond the physical stimulus in a wide range of subjects. What constrains this mental extrapolation? In both cases, the errors seem to predict what is likely to occur in the real world. Both phenomena raise the question of whether external regularities of the world have become internalized in the viewer (perhaps over the course of evolution) and place adaptive constraints on mental extrapolation (Shepard, 1984, 1994).

Consider Shepard's (1984) well-known example of circadian rhythm in animals. He argued that because the circadian behavioural cycle is correlated with the day/night cycle in the world, people initially assumed that it was these stimuli that elicited the biological response. However, when hamsters in laboratories were deprived of external indicators of day or night, their circadian cycle continued in the absence of stimulation. Although individual animals drifted out of phase with one another over time, the basic cycle remained intact. Exposure to light stimulation corresponding to day/night brought them back into alignment with one another. He proposed that mental representation is also guided by internalized constraints about regularities in the world. When the external stimulus is removed the internal system continues. Can this explain RM and BE?

Representational momentum

Freyd and Finke's (1985) choice of the term "representational momentum" reflected the idea that the mental extrapolation was analogous to physical momentum. In terms of Shepard's theory, the characteristics of physical momentum in the physical world were internalized during evolution. Thus, when the inducing stimulus disappears, without this external stimulation (just as in the case of circadian rhythms), the mental representation nevertheless continues (perhaps with some "drift" across individuals). The observation that the amount of the extrapolated shift increased with increases in implied velocity (Finke et al., 1986; Freyd & Finke, 1985), provided support for this conceptualization. Freyd and Johnson's (1987) retention interval effects (described earlier) also showed a striking parallel between representational momentum and physical momentum.

Subsequent research raised questions about this theoretical perspective. For example, RM effects occurred not only for physical motion but also for more abstract "movement" such rising and falling tones (Kelly & Freyd, 1987). High-level expectations, discussed previously (e.g., Hubbard, 1994; Hubbard & Bharucha, 1988) affected the direction of the extrapolated shift. In response to these types of observations, Freyd (1987, 1993) proposed a different theoretical perspective to account for RM and RM-like phenomena. Instead of an internalization of specific regularities experienced in the world (a directional

effect), she argued for a parallel relationship between the physical world and the mental world.

She proposes that RM and related phenomena are a "necessary characteristic" of a representational system with spatiotemporal coherence. The representational system, like the physical world, is a dynamic spatiotemporal system. Just as physical properties of objects are embedded in space and time, the mental representation of these properties is embedded in a spatiotemporal representation. For Freyd (1987, 1993), any dimension that allows a continuous transformation in the world is likely to result in a dynamic representation in the mind of the perceiver. Although subsequent research suggests that some qualification of this claim is necessary because continuous changes in some types of dimension do not yield RM (e.g., luminance: Brehaut & Tipper, 1996 and Favretto, Hubbard, Brandimonte, & Gerbino, 1999; and facial expression: Thornton, 1998), the basic concept nevertheless remains viable (see Bertamini, this issue, for a related discussion).

The central concept of Freyd's (1993) theory is dynamics. Change occurs over time in the external world. She posits that in order to represent that world, mental representations must also include a temporal parameter. Disequilibria of forces in the world convey a mental representation that reflects implied dynamics. This is why, not only moving displays, but also static pictures (Freyd, 1983; Freyd et al., 1988; Futterweit & Beilin, 1994) and works of art (e.g., paintings and sculptures; Freyd, 1993) can convey motion and a sense of dynamic tension. Representations are not snapshots. They are as dynamic as the world itself.

Boundary extension

Whether a perceiver is in an open field or a tightly constrained space, wherever he or she looks, a shift in the position of the eyes will bring a new region into view—the world is continuous. Continuity of layout is a pervasive attribute of the environment (an external regularity), yet the observer can only sample the continuous world successively over time (through eye movements as well as head and body movements). The perceiver can never directly experience his or her surroundings all at once. Physiological constraints place limits on every view of a scene: the visual field has a limited expanse ($180° \times 150°$ of visual angle), high acuity is limited to the foveal region (only $2°$ of visual angle), and in addition, there is the blind spot. Viewers are not usually conscious of the paucity of the sensory input—of the degree to which acuity drops the farther information falls from the tiny foveal region. This may be due in part to the fact that ballistic eye movements can change the point of fixation as rapidly as 3–4 times per second (Irwin, 1991; O'Regan, 1992).

Between saccades, however, vision is suppressed and visual information must be represented in memory—referred to as transsaccadic memory (Irwin,

1991, 1992). Given the tiny region of visual acuity available in each glimpse of the world, and the temporal discontinuity of visual input, adaptive value would accrue to a system that would take advantage of regularities in the environment (such as its continuity), rather than interpret each glimpse of the world anew. Recall that extrapolation of layout seems to occur at least as soon as 1 s following a glimpse of a photograph (Intraub et al., 1996). Perceptual systems have evolved in a world with invariant properties (Gibson, 1950, 1966, 1979). If as Shepard (1984, 1994) proposes, regularities of the world become internalized during evolution, then perhaps, the expectation of continuity is built into the visual system. To incorporate a succession of bounded views into a coherent representation of a continuous world, the visual system may use a variety of extrapolation processes. For example, amodal completion (e.g., Nakayama, He, & Shimojo, 1995) and amodal surface continuation (Yin, Kellman, & Shipley, 1997), allow the visual system to extrapolate beyond the sensory input. Boundary extension may draw upon such processes as well as more high-level knowledge about scenes.

Extrapolation of layout in conjunction with the highly selective input provided by successive views (in which the highest acuity is limited to the foveal region) may together support a coherent mental representation of the viewers' surroundings. This would yield a schematic (non-pictorial) representation of layout and landmarks. The concept of a schematic mental structure guiding successive views is not new (cf., Hochberg, 1986, 1998; von Helmholtz, 1894/1971). Recent research on transsaccadic memory (e.g., Irwin, 1992; McConkie & Currie, 1996) and change blindness (e.g., Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997; also see Hochberg, 1986) has provided more evidence to support this conceptualization. Focal attention to particular objects (or features) can cause them to be incorporated into the mental representation (see Wolfe, 1999), but for the most part, much of what is retained appears to be more "sketchy" than picture-like (Hochberg, 1986; Intraub, 1997; Irwin, 1992; Rensink et al., 1997).

Intraub and her colleagues (e.g., Intraub, 1997; Intraub et al., 1998) have proposed that mental extrapolation beyond the borders of the current view becomes incorporated in the mental representation, resulting in boundary extension. It may be that BE is the product of a visual system that must convey information about the continuous environment, and in so doing "ignore" the spurious boundaries caused by sensory limitation or the momentary occlusion of the view by physical objects or surfaces in the world. (Note that this is true in the case of haptics without vision as well—we cannot feel the continuous environment all at once, and each tactile "glimpse" is bounded by the size of the hand.) The adaptive value of rapidly extrapolating spatial layout would be three-fold. It would serve to: (1) allow the viewer to understand each view within its expected context, (2) facilitate integration (and thus comprehension) of successive views, and (3) help draw attention (and the fovea) to unexpected

features and surface changes that appear in an upcoming view. The ability to rapidly extrapolate spatial layout beyond the current view would allow the observer to understand occluded views (see Intraub, in press).

Intraub and Richardson (1989) argued that without the ability to project beyond the edges of a view during perception, a viewer would misinterpret a photograph of a friend's smiling face as a picture of a disembodied head. Instead, the viewer perceives that friend and the background continue beyond the edges of the photograph. The ability to meld seen information and extrapolated information seems natural in a system that "fills in" the blind spot, and rapidly samples the environment with only a tiny region enjoying high acuity with each fixation. According to this perspective, when we look at a photograph of a scene, the visual system processes the information as if we were looking at the world through a window. We perceive the photograph in the spatial context of what is understood to exist beyond the boundaries of the view.

BOUNDARY CONDITIONS

To test these theoretical perspectives, it is necessary to articulate principled boundary conditions under which RM and BE should not occur.

Representational momentum

According to Freyd's (1987, 1993) theory of dynamic representation, RM and similar effects should not obtain when the stimuli do not convey a smooth transformation over time. Indeed, disrupting the order of the inducing stimuli, such that the coherence of an implied motion is damaged will not yield representational momentum effect (e.g., Freyd & Finke, 1984). Similarly, in frozen motion studies, the same two pictures presented in reverse do not yield an RM-like effect (e.g., Freyd, 1983; Futterweit & Beilin, 1994).

The "state" of the final inducing stimulus also has been shown to determine if RM will occur. When the inducing display shows a moving target coming to a full stop, although there was directional movement in the display just prior to the stop, RM does not occur (Finke et al., 1986). Kelly and Freyd (1987) demonstrated that if the final inducing stimulus in sequence implying rotation was at a good "finishing point" RM did not occur (e.g., a horizontal rather than a tilted position). They also demonstrated the importance of maintaining object identity across an inducing sequence. Successive views of a rotating rectangle yielded RM, but if a new object were presented at each successive rotation, RM did not occur. Clearly, the occurrence of representational momentum is constrained (see also Kerzel, this issue), and in many ways conforms to Freyd's proposal.

Boundary extension

If BE reflects the continuity of spatial layout in the world, then it should occur only in memory for pictures in which the background depicts part of a continuous locale (i.e., a scene). It should not occur in memory for pictures that do not (e.g., a dictionary drawing of an object). To test this, Intraub et al. (1998; also see Legault & Standing, 1992) compared memory for outline-drawn objects presented on a scenic background or on a blank background depicting "nothing". All stimuli were traced from close-up and wide-angle photographs of an object on a natural background. Figure 3 shows the "traffic cone" on a background depicting a location in a scene and on a blank background (close-up and wide-angle versions).

Following Intraub and Richardson's (1989) procedure, subjects were presented with 16 outline scenes or "non-scenes", for 15 s each (half in their close version and half in their wide-angle version) and were tested immediately after presentation by viewing either the same picture (true same) or the opposite version. Subjects rated each test picture on the same type of 5-point scale used in other BE experiments to indicate if the test picture was the same or showed a "closer-view (object bigger)" or a "more wide-angle view (object smaller)".

The results are shown in Figure 4 ("scene" and "object control" conditions). Scenes yielded the typical BE pattern: layout extrapolation for close-ups and no directional distortion for wide-angle views. In contrast, pictures of the same objects on blank backgrounds did not yield boundary extension—they yielded normalization (as predicted by Intraub et al.'s, 1992, extension-normalization
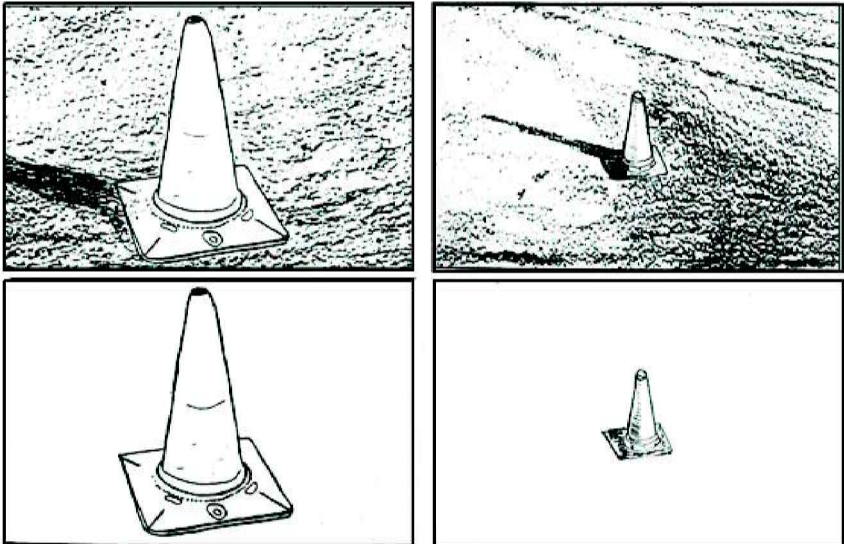

Figure 3.   Example of close-up and wide-angle stimuli used in Intraub et al. (1998). Outline drawings of an object in a scene context (top row) and the same objects on a blank background (bottom row).
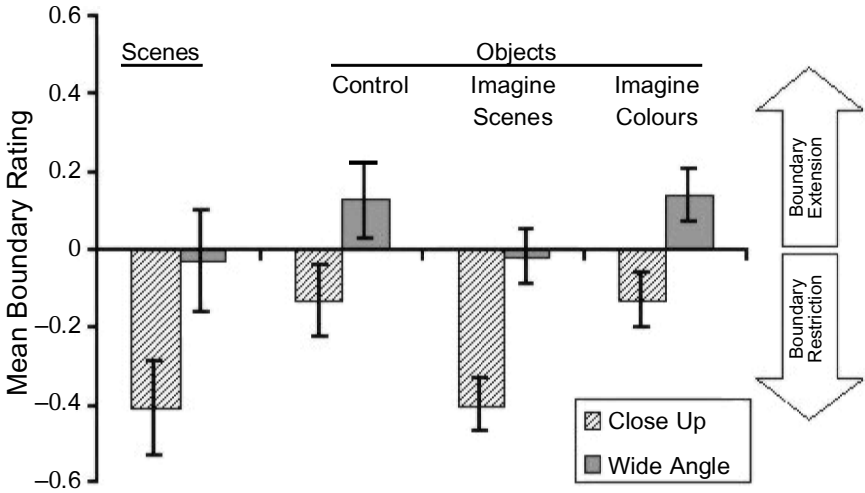
Figure 4. Mean boundary ratings for outline drawings of objects in scene contexts, and for the same objects on blank backgrounds when participants were instructed to: (a) remember without imagery instructions (control), (b) imagine scenic backgrounds (imagine scenes), or (c) imagine the object's colours (imagine colour). Error bars show the 0.95 confidence intervals. Negative scores indicate viewers remember seeing more background (and smaller object), and positive scores indicate they remember seeing less background (and larger object). Graph is based on tables in Intraub et al. (1998).

model). Without the outward "force" of layout extrapolation, a symmetrical normalization pattern occurred: large objects were remembered as smaller and small objects were remembered as larger. (Similarly, consistent with Freyd & Johnson's, 1987, two-component model, normalization has been observed in memory for dimensions that do not evoke RM: Brehaut & Tipper, 1996; Favretto et al., 1999; Thornton, 1998.)

Pictures of objects in scene contexts evoked the pattern of extrapolation seen in numerous boundary extension studies, whereas pictures of the same objects that did not depict a spatial location (i.e., part of a continuous world) did not. Epstein and Kanwisher (1998) have reported a similar distinction between pictures of objects in a location (a "scene") and pictures of objects that were not. They reported a region of the parahippocampal cortex, which they called the "parahippocampal place area," that responded strongly to passively viewed scenes such as empty rooms, furnished rooms, and landscapes, but more weakly to the same objects on blank backgrounds. Although it is highly speculative to suggest that the activation is related to the extrapolation that yields BE, it is noteworthy that our behavioural data and the fMRI data both suggest special activity in the case of a depicted location.

However, scenes and non-scenes also differ in that the scenes included visual information right up to the picture's edges, whereas the non-scenes did not. Perhaps it is this factor, that mediated the occurrence of BE, rather than

scene extrapolation. In two other experiments, Intraub et al. (1998) replicated their findings under conditions in which the scenes and non-scenes were physically identical. They did this by presenting only the objects (blank background) and creating a scene condition through imagery. If the continuity of layout is a fundamental aspect of the mental representation, then it should underlie not only perception, but imagery as well (see Shepard, 1984). The constraints that determine mental representation following perception should similarly constrain imagination.

In the imagine-scene condition, subjects were told that the objects they were about to see were traced from real photographs and to help them remember the sizes of those objects, the experimenter would provide a brief description of the associated photograph (e.g., "the traffic cone is on an asphalt road and is casting a shadow on the left"). They were instructed to mentally "project" an image of the described background onto the stimulus. In the imagine-object condition, everything was the same except that viewers were provided with descriptions of the objects' colours instead (e.g., "the traffic cone" is bright orange with a black base) and were instructed to mentally "project" those colours onto the object. This served two purposes: (1) it controlled for possible effects of imagery instructions per se on memory, and (2) unlike the first experiment, it allowed us to contrast a scene condition with an object condition holding the stimuli and test pictures constant.

The results are shown in Figure 4 (imagine conditions). Imagining the background yielded the same pattern of results as actually viewing scenes (the scores are virtually identical), whereas imagining the objects' colours once again yielded the normalization pattern (again, virtually the same as in the control condition). Gottesman and Intraub (2001) found a similar pattern of results when they biased the observer's construal of a blank background in a display as being a truncated view of a scene or an unrelated blank piece of paper. In light of the imagery findings, it is interesting to note that in another fMRI study O'Craven and Kanwisher (2000) have found that imagining locations also causes relatively high activation in the "parahippocampal place area" (Epstein & Kanwisher, 1998), as compared with imagining faces.

Generality of RM and BE

Finally, do these examples of anticipatory mental extrapolation generalize to situations in real 3-D space (rather than 2-D pictures and displays) and/or to other sensory modalities beside vision?

Representational momentum. Although frozen motion studies have used photographs of natural scenes (as discussed earlier), RM studies have not. Studies of representational momentum following movement of objects in real 3-D space have yet to be implemented. It has not yet been determined whether

RM would occur for moving objects under these rich viewing conditions. In his discussion of Shepard's (1994) evolutionary theory of internalized regularities, Schwartz (in press) questions the ecological validity of Shepard's choice of apparent motion tasks as the primary means of testing internalized constraints. He questions whether observations made under these unusually impoverished conditions can be assumed to generalize to the mental representation of motions in a richly structured world. Similar cautions can be applied in the analysis of RM and its implications.

Especially as the number of types of displacement errors have proliferated (e.g., representational gravity, representational friction, landmark effects: see Hubbard, 1995b, Hubbard & Ruppel, 1999), it seems important to test memory in richer, more natural displays. The dramatic effect of scene backgrounds and blank backgrounds on the presence or absence of boundary extension (Intraub et al., 1998), and Verfaillie's (1997) observation that not simply the presence of a landmark, but the presence of landmarks that could be perceptually grouped affected detection of changes across saccades, make this seem a wise course of action. The value of the current research using uncomplicated stimuli on blank backgrounds is unquestioned, but parallel research with more natural and complex scenes could either provide strong additional support for current hypotheses, or perhaps important caveats that would help define the principles underlying these dynamic phenomena.

However, the generality of RM has clearly been shown in the sensory domain. Representational momentum has been demonstrated with auditory stimuli. Kelly and Freyd (1987), for example, demonstrated that rising and falling pitches result a displacement along the "path of motion" when remembering the final pitch. Error rates and reaction times to make same/different judgements to the test tone, were analogous to those obtained with implied motion of visual stimuli. Hubbard reported similar effects on the representation of pitch, and has also reported velocity effects analogous to those found in vision (see Hubbard, 1993, 1995a).

Boundary extension.   Until recently, research on BE has only tested spatial memory for pictures of scenes. New research (Intraub, 2001) has begun to address the question of whether BE is a representational error that occurs in picture memory, or if it reflects fundamental aspects about memory for scenes that would apply to representation of common scenes in the 3-D world. To this end, we created two sets of six–seven real scenes in the laboratory in which real objects were arranged on natural backgrounds (e.g., a kitchen scene—utensils, pot, potholder, measuring spoons on a table top). We exposed a rectangular region of each scene, occluding the surrounding area with black cloth (creating a "window" effect).

In one experiment (Intraub, 2001), 20 subjects viewed six such scenes for 30 s each with the occluding window in place. Subjects then waited in another

room while the window was removed. They returned and marked off how much of each scene they had viewed previously. The occluding material was placed at the designated locations and the subjects made any necessary adjustments to recreate the view they had studied minutes earlier. The width and length of the window they created was measured. In the case of each scene, the window set by the subject showed more of the surrounding area than they had originally seen. The average increase in area ranged from 28% to 94% across the six scenes.

The effect generalized to haptic exploration as well. Sizeable amounts of boundary extension were also obtained when blindfolded subjects explored the same bounded scenes with their hands for the same length of time. In this case the "window" was formed from four wooden borders and the subjects were instructed to feel the entire region within the "frame", without touching anything outside the borders. The borders were removed and subjects re-explored each scene, indicating where the borders had been. As in the case of vision, subjects tended to extend the boundaries of the region—increasing the area 11–29% across scenes.

Haptic subjects may have been recruiting visual resources when representing the scenes (e.g., visualization). To address this possibility and provide a better test of haptic input alone, the same scenes were explored by a woman who has been deaf and blind since early life due to a genetic disorder (Leber's syndrome). Although she relies upon haptic input in her interactions with the world, and her communication (Braille, and American Sign Language), she too remembered the scenes with extended boundaries, in most cases extending them as much or more than the sighted-blindfolded subjects. In only one case did she show a lesser degree of extension. As discussed previously, rather than an error, BE appears to be a good prediction about the spatial context of a partial view of the continuous world. In other research (Intraub, Turner, & Clement, 1999) we showed the same effect for visual and haptic exploration using the same test procedure, and using a recognition procedure. These results demonstrate that BE occurs in the context of the rich cues provided in the 3-D world, and is not limited to the visual sense.

CONCLUSIONS

Do the same underlying mechanisms serve both phenomena?

Hubbard (1995b, 1996) was the first to offer a specific analysis of the relationship between RM and BE. He did this in the context of RM research on simulated movement in depth: The inducing stimuli were outline squares that increased or decreased in size such that they appeared to represent movement toward and away from an observer. He argued that one could view BE as a

displacement in depth. When BE occurs, objects are remembered as covering a smaller area in the picture space, a factor that he pointed out is "geometrically equivalent to a displacement of the target away from the observer" (p. 333). This in conjunction with other similarities between the phenomena (e.g., dynamic, unidirectional, greater extrapolation when tested immediately than after a delay), led him to suggest that BE and RM "may arise from either similar mechanisms or different facets of the same general displacement mechanism" (p. 334). According to this account, BE involves a displacement in depth (away from the observer).

Intraub and Richardson (1989) also recognized that BE might reflect changes in remembered distance ("the view is farther away"), or changes in remembered expansiveness ("I saw more of the scene"). Over the years, my colleagues and I have favoured the latter alternative—focusing on layout. Initially, this was because it seemed to possess greater explanatory power. The adaptive value of anticipating layout just outside the current view seemed readily apparent (described previously in the section on "Theoretical Perspectives"). The adaptive value of consistently representing objects as farther away was not apparent, and instead seemed somewhat counterproductive. After all, our interaction with the world involves both moving toward and moving away from objects. However, in support of the "layout" interpretation, even when standing still (not moving closer or father from an object) small movements of the eyes and head bring more of the world into view.

Recent research on BE in the 3-D world (in which distance is not confounded with expansiveness of the view) tends to support the "layout" alternative (Intraub, 2001). After exploring scenes visually or haptically (while blindfolded), when they returned to the same location in front of the scenes, subjects did not step back from the scene indicating a displacement in depth, but stayed in the same location and marked off a greater expanse of the scene. So although I share Hubbard's interest in the many attributes that RM and BE do seem to share in common, I do not think it likely that they share a common displacement mechanism. Boundary extension does not seem to be a displacement in depth.

Do RM and BE reflect the same principles of representation?

The ability to anticipate is fundamental to normal perception and action. At the behavioural level, speech errors (e.g., Spoonerisms) and motor errors in skilled motor tasks (e.g., typing) indicate implementation of action plans in advance of execution (Rosenbaum & Krist, 1996; Wright & Landau, 1998). At a neural level, there is evidence from single cell recordings of visual cells in macaque parietal cortex, that when a saccade is planned, a cell's receptive field can adjust to include the to-be-fixated region (Colby, 1996; Colby & Goldberg,

1999). RM and BE show that anticipatory projections are part of the mental representation of complex spatiotemporal events.

In RM spatiotemporal coherence of the mental representation reflects dynamic tensions in the world (Freyd, 1993). BE reflects the spatiotemporal aspects of spatial cognition. In vision, the eyes scan a spatial expanse bringing the fovea to new regions as quickly as four times per second. In haptic exploration (without vision), the hands bring successive regions to the observer. The cognitive system must convey the continuity of real-world layout through successive sampling over time. Representational momentum and boundary extension appear to be related in the sense that they are both examples of the predictive, dynamic nature of mental representation.

Freyd (1993) captures the essence of RM and related phenomena, as well as viewers' responses to works of art in this way "lurking behind the phenomenal sense of concreteness one has when viewing some pictures or scenes may be an underlying representation of physical forces" (p. 105). This also seems to capture important aspects of boundary extension. The difficulty however, lies in how to define "forces". What dynamic forces are out of balance in the picture of trash cans in Figure 2?

Following Freyd's (1993) appeal to the world of art, a possible answer is suggested by a commonly used device in cinematography. A film-maker can heighten suspense by maintaining a tight close-up while panning. For example, the filmgoer suspects something terrible might have happened in a room. The camera focuses in on a patch of carpeting and begins to roam, showing perhaps a shoe here, and a partial shadow there, but not providing a wide enough view to provide an immediate understanding of what (if anything) has transpired. The roaming close-up imparts a strong sense of tension—the viewer's periphery is occluded and his/her normal act of visual scanning is prevented. Although not typically as dramatic as the movie scenario, tight close-ups do seem to convey a sense of tension. When the view is occluded, sensory input stops at the border, but the mental representation does not. This yields a dynamic representation of an otherwise stationary view in which extrapolation of the periphery is enacted.

However, this interpretation (involving the tension inherent in a close-up) might stretch Freyd's (1993) concept of "dynamic forces" too far. A somewhat different slant on these ideas is to focus primarily on change over time in the act of visual or haptic exploration. In the case of RM, the change (real or implied) is in the stimulus itself. The observer is "outside" the movement. In the case of BE, the change over time refers to the perceiver's anticipated movement in scanning the scene. Even while looking at a still scene, the act of perception itself is dynamic. The observer actively explores the scene, rapidly shifting the focus to different spatial locations. The perceiver is not "outside" the movement, but is moving (e.g., shifting fixation, moving his/her hands) in order to perceive. When viewing a bounded scene (bounded by the edges of a picture, a

window frame, or even the borders of the visual field itself), the dynamic act of perceiving is limited by occlusion, but the dynamics inherent in the representation are not. This results in boundary extension, much as the dynamic act of an object moving across space is stopped when the object vanishes, but continues in the observer's representation yielding RM.

SUMMARY

There are many intriguing parallels between representational momentum and boundary extension. Dissimilarities in the apparent source of the extrapolation make it seem unlikely that they share a common underlying mechanism, as proposed by Hubbard (1995b, 1996). Instead, these phenomena may be related at a more general level. I have suggested two ways in which Freyd's (1987, 1993) theory of dynamic representation might underlie both. Until constructs such as dynamic "forces" can be more fully defined, however, this connection remains speculative. A more conservative statement of the connection between RM and BE is that they both reflect anticipatory representations of spatiotemporal information. Both demonstrate that the mental representation of a spatiotemporal event is dynamic, incorporating not only the present and the immediate past, but also the immediate future as the perceiver interacts with the world.

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