SECCIÓN EXPERIMENTAL

Psicológica (2006), 27, 1-34.

Bridging the Gap: Possible Roles and Contributions of Representational Momentum

Timothy L. Hubbard*

Texas Christian University, USA.

Memory for the position of a moving target is often displaced in the direction of anticipated motion, and this has been referred to as *representational momentum.* Such displacement might aid spatial localization by bridging the gap between perception and action, and might reflect a second-order isomorphism between subjective consequences of environmentally invariant physical principles and the functional architecture of mental representation that can be modulated by an observer's expectations (e.g., that a moving target will change its heading) or by the presence of nontarget stimuli (e.g., landmarks). Representational momentum and related types of displacement reflect properties of the world and properties of mental representation, and so a consideration of representational momentum and related types of displacement contribute an important component of contemporary psychophysics, and also broaden the reach of psychophysics to include numerous topics not usually considered within psychophysics (e.g., naive physics, boundary extension, flash-lag effect, aesthetics, mental imagery).

Memory for the final position of a moving target is usually displaced slightly forward in the direction of motion, and this has been referred to as *representational momentum* (Freyd & Finke, 1984; for a sampling of recent research, see Thornton & Hubbard, 2002). Representational momentum might reflect an important aspect of the relationship between physical

---

* This article is based on presentations at Visual Localization in Space-Time (Brighton, United Kingdom, August 2002) and Visual Space Perception and Action (Ohlstadt, Germany, September, 2002). The author thanks Antonio Asnar Casanova, David Travieso Garcia, J. F. Juola, Dirk Kerzel, Jose Aparecido da Silva, and two anonymous reviewers for helpful comments on an earlier version of the manuscript. Correspondence should be addressed to Timothy Hubbard, Department of Psychology, TCU Box 298920, Texas Christian University, Fort Worth, TX 76129, USA. Electronic mail may be sent to t.hubbard@tcu.edu

properties of the world and the way the mind represents those properties, and so the study of representational momentum is an important component of research and theory development in contemporary psychophysics and cognitive science. Representational momentum and some related types of displacement will be briefly reviewed; it is suggested that such biases in spatial representation originate from a second-order isomorphism between subjective consequences of invariant physical principles and mental representation, and that such biases can be modulated by an observer's expectations or by the presence of nontarget stimuli. Also, representational momentum is suggested to help bridge the gap between perception and action by adjusting the mental representation of a target to reflect where that target would be when an immediate response from an observer would reach the target, and might help bridge the gap between traditional psychophysics and many other areas of investigation.

Part I: An Overview of Representational Momentum and Related Displacements

Many researchers have used the term "representational momentum" to refer to any displacement of the remembered position of a previously viewed moving target from the actual previous position of that target. However, displacement is influenced by a number of variables other than the implied momentum of a target (for review, Hubbard, 1995b, in press-b), and the term "representational momentum" does not accurately describe a combination of momentum and non-momentum variables, nor does it distinguish between effects of implied momentum and effects of other variables. Also, remembered position can be displaced in directions other than the direction of motion (e.g., along the axis orthogonal to motion, Hubbard & Bharucha, 1988), and the term "representational momentum" does not accurately describe displacement in those other directions. For these reasons, Hubbard (1995b) suggested the broader term "displacement" should be used to refer to general mislocalizations in memory for target location, and the more specific term "representational momentum" should only be used to refer to that component of displacement that reflects the influence of implied momentum.

Representational Momentum

In the initial demonstration of representational momentum, Freyd and Finke (1984) presented three sequential concentric static presentations of a rectangular target (see top of Figure 1), and these stimuli were referred to as the *inducing stimuli*. A fourth concentric static rectangle, referred to as the *probe*, was then presented. The orientation of the probe was either the same as that of the final inducing stimulus or rotated slightly forward or backward from the orientation of the final inducing stimulus, and observers judged whether the orientation of the probe was the same as or different from the orientation of the final inducing stimulus. When the inducing stimuli within a trial implied motion in a consistent direction, observers were more likely to respond "same" to probes rotated slightly forward than to probes rotated slightly backward (see bottom of Figure 1). Freyd and Finke (see also Finke, Freyd, & Shyi, 1986) suggested this pattern resulted from an internalization of the effects of momentum, and so they referred to the forward displacement as *representational momentum.* Other explanations of representational momentum have subsequently been proposed (for review, see Hubbard, in press-a), and include spatiotemporal coherence (Freyd, 1987), an influence of implicit knowledge (Hubbard, 1998a), a belief in impetus (Kozhevnikov & Hegarty, 2001), and oculomotor behavior (Kerzel, 2000).

Hubbard and Bharucha (1988) presented a computer-animated target undergoing horizontal or vertical motion that appeared continuous and smooth, and after the target vanished, observers used a computer mouse to place the cursor at the display coordinates at which that target vanished. The displacement between the judged vanishing position and the actual vanishing position was measured. Observers placed the cursor at a position slightly beyond (i.e., in front of) where the target had actually vanished (see top of Figure 2), and this forward displacement increased with increases in target velocity and was larger for horizontally moving targets than for vertically moving targets (see also Hubbard, 1990). The forward displacement observed by Hubbard and Bharucha was similar to that observed by Freyd and Finke, and this provided useful convergent evidence that forward displacement is a more general phenomenon and not limited to a specific stimulus type or response method. Along these lines, it is useful to note that neither implied motion nor continuous motion is necessary in order to evoke forward displacement, as observers shown a still photograph drawn from a larger action sequence are more likely to accept a photograph drawn from later in the sequence than a photograph drawn from earlier in the sequence as being the same as the initially viewed photograph (e.g., Futterweit & Beilin, 1994).

In the years since these initial studies, numerous studies of forward displacement in general and of representational momentum in particular have been reported. A complete review of this literature is beyond the intent or scope of this article (for reviews, see Hubbard, 1995b, in press-b), but a brief listing of some factors that influence displacement in the direction of motion would include target velocity (Freyd & Finke, 1985; Hubbard & Bharucha, 1988) and acceleration (Finke, Freyd, & Shyi, 1986), target shape (Nagai & Yagi, 2001), direction of target translation (Hubbard, 1990), axis of target rotation (Munger, Solberg, Horrocks, & Preston, 1999), direction of target motion relative to a landmark (Hubbard & Ruppel, 1999), motion of the surrounding context (Hubbard, 1993), expectations regarding a change in the direction of target motion (Hubbard & Bharucha, 1988; Johnston & Jones, in press; Verfaillie & d'Ydewalle, 1991), attribution of the source of target motion (Hubbard & Favretto, 2003; Hubbard & Ruppel, 2002), conceptual knowledge regarding the identity of the target (Reed & Vinson, 1996; Vinson & Reed, 2002), retention interval (Freyd & Johnson, 1987), allocation of attention (Hayes & Freyd, 2002; Kerzel, 2003a), activation of motor action plans (Jordan, Stork, Knuf, Kerzel, & Müsseler, 2002; Jordan & Knoblich, 2004), and for the special case of a smoothly moving target, whether observers visually track the target or fixate a nontarget location (Kerzel, 2000, 2002c; Kerzel, Jordan, & Müsseler, 2001).

Representational Gravity

Hubbard and Bharucha (1988) reported that memory for horizontally moving targets was also displaced downward and that forward displacement of descending targets was larger than forward displacement of ascending targets (see top of Figure 2). Hubbard (1995b, 1997) suggested these displacement patterns were consistent with effects of gravity on physical objects (i.e., unpowered horizontally moving objects fall along a parabola, descending objects accelerate as they fall, ascending objects decelerate as they rise), and so referred to this as *representational gravity*. Forward displacement for vertically moving targets is smaller for targets higher in the picture plane (i.e., ascending objects that have risen a longer distance, descending objects that have fallen a shorter distance), and this pattern suggests displacement is influenced by implied acceleration or deceleration due to implied gravity (Hubbard, 2001). Effects of representational gravity are observed with stationary targets (Freyd, Pantzer, & Cheng, 1988), depend upon the external environmental axes rather than the body axis or the orientation of the body axis relative to the external environment (Nagai, Kagai, & Yagi, 2002), occur regardless of whether observers visually track a smoothly moving target or fixate elsewhere (Kerzel et al., 2001), and can be observed even in conditions of weightlessness (McIntyre, Zago, Berthoz, & Lacquaniti, 2001).

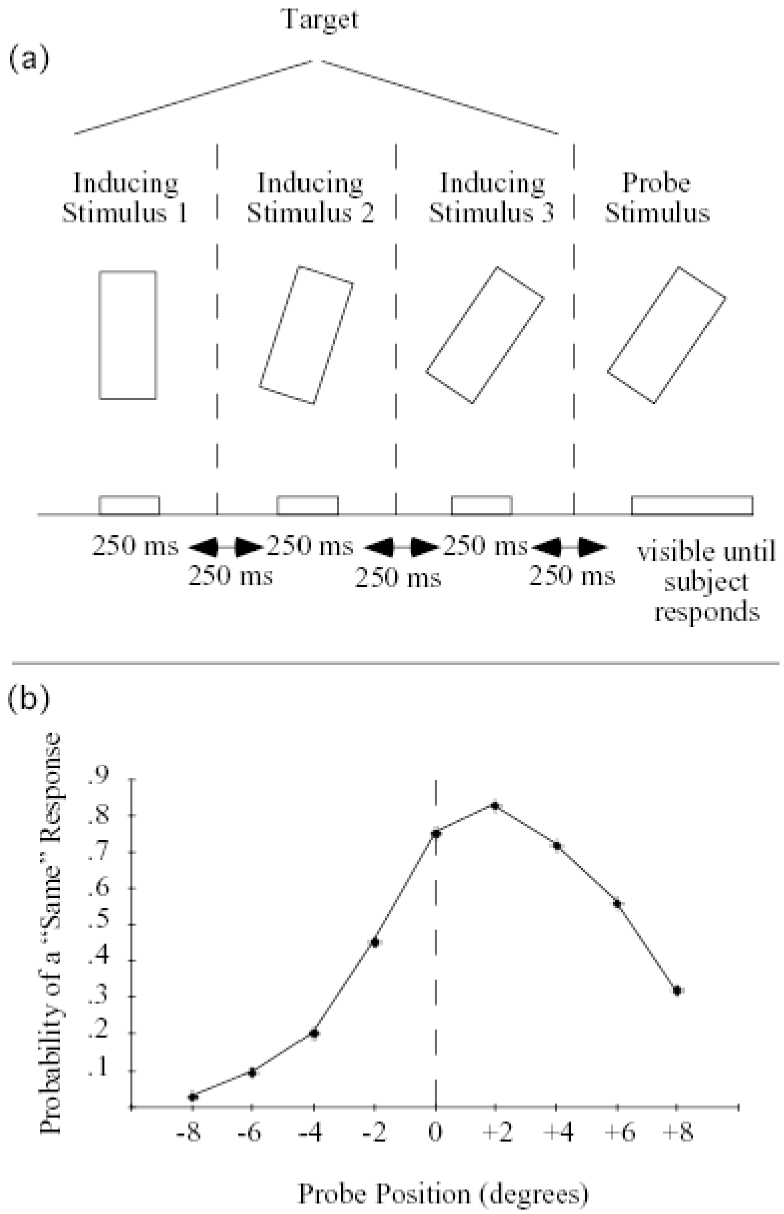

Figure 1. The experimental methodology and results from Freyd and Finke (1984). Panel (a) illustrates a trial in which three inducing stimuli and a probe are presented. Panel (b) illustrates the probability of a "same" response as a function of probe orientation relative to the final inducing stimulus. The dashed line is the "true-same" orientation of the final inducing stimulus, negative probes were rotated backward from the orientation of the final inducing stimulus by the indicated number of degrees, and positive probes were rotated forward from the orientation of the final inducing stimulus by the indicated number of degrees. Representational momentum is indicated by the higher probability of a "same" response to positive probes.

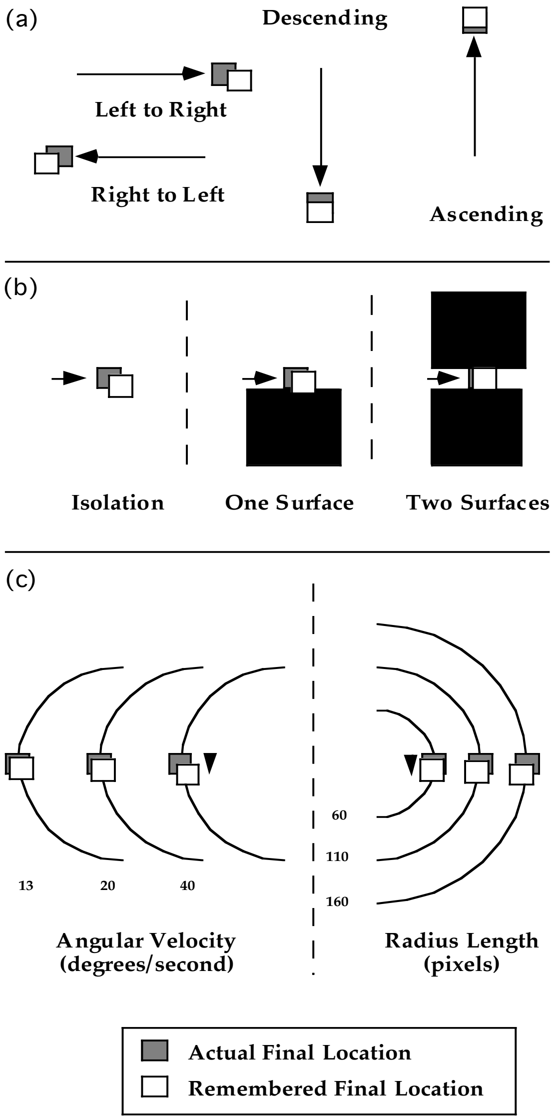

Figure 2. **Typical findings from studies of representational momentum, gravity, friction, and centripetal force. In panel (a), representational momentum is indicated by forward displacement of remembered position, and representational gravity is indicated by downward displacement for horizontally moving targets and larger forward displacement for descending targets than for ascending targets. In panel (b), representational momentum is indicated by forward displacement of remembered position, and representational friction is indicated by decreases in forward displacement with increases in implied friction. In panel (c), representational momentum is indicated by forward displacement of remembered position along the tangent, and representational centripetal force is indicated by inward displacement of remembered position toward the center of the circular path. Adapted from Hubbard (in press-b).**

Representational Friction

If a moving target slides along a single larger stationary surface, forward displacement of that target is decreased. If the amount of implied friction is increased even more by having the target slide between two larger stationary surfaces, forward displacement of that target is decreased even more (see middle of Figure 2). In general, forward displacement of a target decreases as the amount of implied friction on that target increases (Hubbard, 1995a, 1998b). Given that increases in physical friction produce decreases in physical momentum, these patterns are consistent with the existence of *representational friction.* Interestingly, decreases in forward displacement can be observed even if targets do not actually change velocity upon encountering implied friction, and this suggests the effect of representational friction is quite robust: observers respond as if targets decelerate upon encountering implied friction, even if targets do not decelerate. The decrease in forward displacement with increases in implied friction is larger if observers fixate the target rather than the friction surface (Kerzel, 2002c). Also, findings that pointed targets can exhibit greater forward displacement than do nonpointed targets (Nagai & Yagi, 2001) are consistent with representational friction, because pointed targets would be more streamlined and less susceptible to effects of friction with any medium the target moved through than would nonpointed targets.

Representational Centripetal Force

Hubbard (1996b) reported that memory for the location of a target moving along a circular orbit was displaced forward along the tangent and inward toward the focus of the orbit, and the magnitudes of forward and inward displacement increased with increases in radius length and with increases in angular velocity (see bottom of Figure 2). Forward displacement along the tangent is consistent with representational momentum, and inward displacement toward the focus is consistent with the existence of *representational centripetal force.* Kerzel (2003b) replicated these forward and inward displacements, and also reported that when observers fixated the target, forward displacement was relatively large and inward displacement was relatively small, whereas when observers fixated the focus, forward displacement was relatively small and inward displacement was relatively large. Freyd and Jones (1994) presented a target that moved through a spiral tube, and after exiting the tube, the target moved along either a straight, curved, or spiral path and then vanished. Forward displacement was largest for targets that moved along a spiral path after exiting the spiral tube, and this could reflect a summation or averaging of representational momentum and representational centripetal force.

Why Are Such Displacements Interesting?

The examples of displacement discussed thus far suggest the remembered final position of a previously viewed target is often displaced in ways consistent with how physical principles influence a physical object. The presence of such displacement is interesting for at least three reasons. First, a primary function of perception and of cognition is presumably to accurately represent the environment within which an observer is located and to facilitate interaction of the observer with stimuli within that environment. Therefore, the presence of systematic biases in mental representation would not be expected. Second, the nature of physical representation more generally (e.g., as in painting, sculpture, photography) is such that a representation of a stimulus usually does not incorporate or internalize analogues of physical principles that would have acted on the referent physical stimulus (e.g., a photograph of a collision would not incorporate or internalize the force of that collision into the photograph). Therefore, the presence of an apparent analogue of physical principles in mental representation would not be expected. Third, given that physical principles such as momentum have been invariant across the experience of the individual and the species, it is possible that effects of such physical principles helped shape the functional properties of our representational system. Therefore, approaches to spatial perception and cognition that focus solely on environmental invariants or focus solely on mental representations are incomplete.

Part II: Toward a Representational Theory of Displacement

The information processing framework underlying traditional psychophysics and contemporary cognitive science suggests information at one level, structure, or domain is mapped onto information at another level, structure, or domain. A basic question regarding any such mapping involves how information is represented within different levels, structures, or domains; in the case of representational momentum and related types of displacement, this question involves how (or whether) properties of the physical world are mapped onto properties of mental representation. A mapping between elements of two different levels, structures, or domains, and in which relationships, information, or properties within the first domain are preserved within the second domain is referred to as an *isomorphism.* Shepard (1975; Shepard & Chipman, 1970) has written extensively about the possibilities of isomorphism between physical stimuli and mental representation, and he distinguished between first-order isomorphism and second-order isomorphism. In *first-order isomorphism*, characteristics of a physical stimulus would literally be present in the representation of that stimulus (e.g., a mental representation of a green elephant would be green and shaped like an elephant), whereas in *second-order isomorphism*, characteristics of a physical stimulus would be preserved in a more abstract or functional way (e.g., information regarding distances between different points on an object would be preserved by differences in the times required to scan between those points in a visual image of the object).

Physical Principles and Second-Order Isomorphism

The relationship between a physical object and the mental representation of that object is clearly not a first-order isomorphism (e.g., the visual image of a rotating physical object does not involve neurons that are physically rotating). Similarly, the relationship between invariant physical principles that might operate on a physical object and the mental representation of that object is clearly not a first-order isomorphism (e.g., the mental representation of left-to-right motion does not involve neurons that are physically moving from left-to-right). Thus, displacement in the remembered physical location of a target does not involve a first-order isomorphism in which the structure of the brain literally mirrors the structure of the target or any changes in the structure of the target. Rather, displacement is more suggestive of a second-order isomorphism between mental representation and the physical world (and physical principles) in which functional properties of the physical world are preserved or recreated within mental representation and mental representations act "as if" they were influenced by physical principles[1]. Much as Shepard (1975; Shepard & Chipman, 1970) suggested that visual imagery might reflect second-order isomorphism between properties of physical objects and properties of visual images of those objects, it can also be suggested that representational

---

[1] The claim that the representational system appears to respond "as if" influenced by physical forces should not be taken as suggestive of dualism; mental representations are created within the brain, and the brain is a physical device subject to physical laws. Rather, the point is more subtle: the incorporation of the effects of environmentally invariant physical principles into mental representation takes the form of an automatic extrapolation in which mental representation is biased (i.e., displaced) in ways consistent with the subjective consequences of those physical principles.

momentum and related types of displacement might reflect second-order isomorphism between properties of physical principles and properties of mental representation (see also Hubbard, 1999).

The nature of such a second-order isomorphism is illustrated in Figure 3. A physical object that rotates from orientation A to orientation C must pass through an intermediate orientation B, and this reflects a constraint on physical transformation. Similarly, the mental representation of an object that rotates from orientation A* to orientation C* must pass through an intermediate orientation B* (Cooper, 1975, 1976), and this reflects a constraint on mental transformation (Shepard, 1981). The mental transformation is thus a functional analogue of the physical transformation, that is, mental rotation is second-order isomorphic to physical rotation. Although previous discussions of second-order isomorphism focused on preservation of spatial information (e.g., passing through intermediate orientations), the idea of second-order isomorphism is consistent with preservation of information involving invariant physical principles. For example, a physical object that rotates from orientation A to orientation C must also possess momentum, and this reflects a constraint on physical transformation. The mental representation of an object that rotates from orientation A* to orientation C* (e.g., the inducing stimuli in Freyd & Finke, 1984) would thus exhibit a functional analogue of momentum, and such a functional analogue would be (consistent with) representational momentum. Information regarding other invariant physical principles would impose analogous constraints on physical objects and physical transformations that would be reflected in the constraints on mental representation.

Limitations of Second-Order Isomorphism

One limitation to an account of displacement based solely on second-order isomorphism is that second-order isomorphism appears to reflect subjective consequences of physical principles within observers' everyday experience rather than objective physical principles per se. There is ample empirical evidence that objective physical principles have not been incorporated into mental representation. For example, an incorporation of objective physical momentum into mental representation would predict that factors that influence physical momentum would influence representational momentum. Physical momentum is the product of a target's mass and velocity, and so an incorporation of objective physical momentum into mental representation predicts that representational momentum for a given target should be influenced by that target's implied mass and implied velocity. Although the predicted effect of implied velocity has been found (e.g., Freyd & Finke, 1985; Hubbard & Bharucha, 1988; Munger & Owens, 2004), the predicted effect of implied mass has not been found (e.g., Cooper & Munger, 1993; Hubbard, 1997). An effect of mass is not found along the axis of motion, but is found only along the axis aligned with the direction of implied gravity. Given that within the constant terrestrial environment observers typically have not had to distinguish between mass and weight, mental representation appears to reflect the effect of subjectively experienced weight rather than the effect of objective mass.

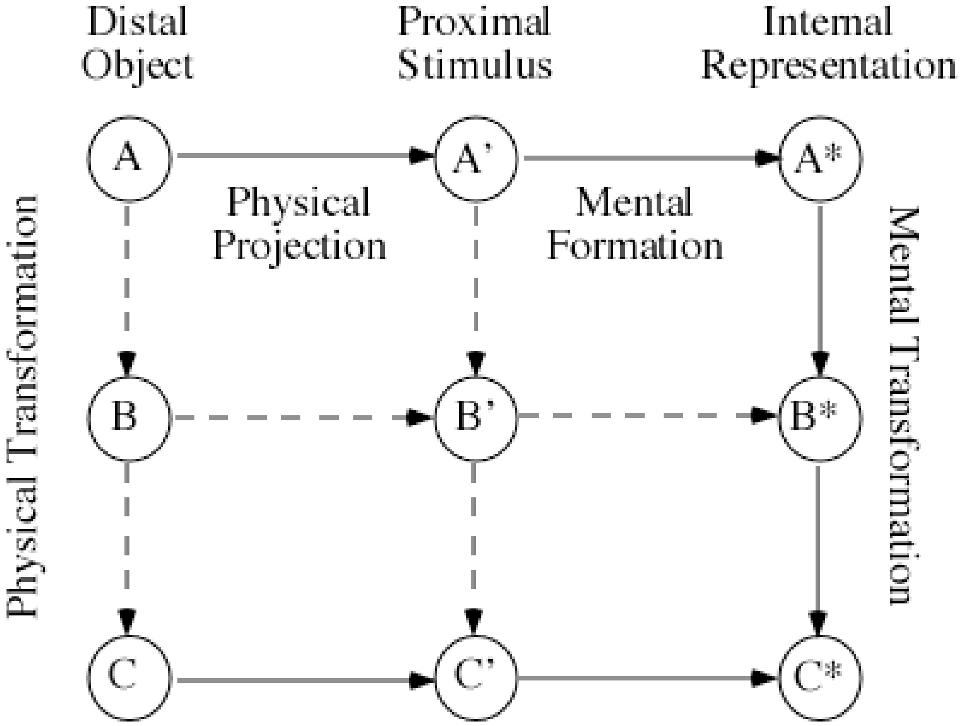

Figure 3. Shepard's illustration of the correspondence between mental and physical transformations. A distal physical object at orientation A must pass through intermediate orientation B before reaching orientation C. Similarly, a mental (i.e., internal) representation of an object in orientation A* must pass through orientation B* before reaching orientation C*. The mental representation of the physical transformation is a functional analogue of the physical transformation (i.e., mental rotation is second-order isomorphic to physical rotation). Similarly, a distal physical object rotating from orientation A to orientation C must exhibit momentum, and so mental representation of a physical object rotating from orientation A* to orientation C* must exhibit a functional analogue of momentum (i.e., representational momentum). Adapted from Shepard and Cooper (1982).

Another limitation to an account of displacement based solely on second-order isomorphism can be found in the effects of context on displacement (for review, see Hubbard, in press-b). At least two types of context can be distinguished: cognitive context, in which an observer's beliefs, knowledge, or expectations influence displacement, and physical context, in which the presence and relative location of nontarget stimuli influence displacement. An observer's beliefs, knowledge, or expectations regarding the motion of a physical target do not influence the physical momentum of that target, and so if representational momentum resulted from an incorporation of objective physical momentum into mental representation, then an observer's beliefs, knowledge, and expectations regarding the motion of a physical target should not influence the representational momentum of that target. However, such cognitive context can influence displacement even when a physical display is held constant and expectations are manipulated by changes in verbal cues (Hubbard, 1994). Similarly, whether a physical target is moving toward or away from a physical landmark should not influence the physical momentum of that target, but such physical context does influence displacement of that target (Hubbard & Ruppel, 1999). To the extent that cognitive or physical context influences displacement of a given target, such displacement does not result solely from second-order isomorphism.

A Two Factor Approach to Displacement

The discussion thus far suggests displacement results from two factors. The first factor involves subjective consequences of invariant physical principles, and reflects second-order isomorphism between subjective consequences of the properties of physical principles on physical objects and properties of the mental representation of physical objects. This provides a default value for displacement, and in the absence of other context (e.g., as when the target is a geometric shape in an otherwise blank display), this default value determines the direction and magnitude of displacement[2]. The second factor involves the presence of cognitive or

---

[2] Kerzel (2000, 2002c, 2003b) has argued against an account of displacement that posits internalization or incorporation of physical principles, and his primary argument focuses on findings that fixation on a stationary location decreases or eliminates forward displacement of a continuously moving target. However, the explanations based on oculomotor behavior that Kerzel appears to favor cannot account for findings that representational momentum occurs with implied motion stimuli (e.g., Freyd & Finke, 1984; Munger, Solberg, & Horrocks, 1999) and with frozen-action photographs (e.g., Freyd, 1983; Futterweit & Beilin, 1994), and cannot account for findings that representational momentum occurs with auditory stimuli (regardless of whether the eyes track a sound source location, e.g.,

physical context that can modulate this default value. If such context is present, then the direction and magnitude of displacement would reflect a combination of the default due to invariant physical principles and the additional context. A brief list of types of context shown to influence displacement would include the presence of nontarget objects (Hubbard & Ruppel, 1999; Kerzel, 2002b), surrounding objects (Gray & Thornton, 2001; Hubbard, 1993), mental set induced by verbal instructions regarding probable target behavior (Hubbard, 1994), expectations developed from viewing previous trials (Kerzel, 2002a) or the higher-order event structure within a single trial (Hubbard & Bharucha, 1988; Johnston & Jones, in press; Verfaillie & d'Ydewalle, 1991), conceptual knowledge regarding target identity (Reed & Vinson, 1996; Vinson & Reed, 2002), and attributions regarding the source of target motion (Hubbard & Favretto, 2003; Hubbard & Ruppel, 2002).

Part III: A Bridge Between Perception and Action

Why would displacement consistent with subjective consequences of invariant physical principles occur? And why might that displacement be modulated by physical or cognitive context? One possible answer is that displacement aids in the spatial localization of physical objects. Accurate localization is important for calibrating an observer's response to an object so that a maximally effective or adaptive interaction with that object can be achieved. Consider the example of an observer attempting to intercept a moving target (see Figure 4). When a moving target is initially sensed, it will be at a specific position in space. The initial sensation will trigger a sequence of perceptual, cognitive, and perhaps motor processes. These neural processes are extremely rapid, but they do take a minimum amount of time. During this time, the moving target does not pause motionless waiting for the observer's neural processing to be completed; rather, the target continues to move. If an observer's response to such a target is to be maximally effective (e.g., if that observer is to successfully intercept the moving target), then that response should be tailored to the target as that target will be at the moment the response would reach it, not as that target

---

Getzmann, 2005) or tactile stimuli (e.g., Brouwer, Franz, & Thornton, 2004). Furthermore, displacement is clearly influenced by higher-order cognitive processes (for discussion, see Hubbard, in press-b). Although explanations of displacement that are based on oculomotor behavior are consistent with the narrow range of data involving forward displacement of continuously moving visual targets, such explanations do not appear consistent with the much broader range of data involving other types of stimuli and top-down effects on displacement (for discussion, see Hubbard, in press-a,b).

was when it was initially perceived. In other words, if an observer's response is to achieve the desired result, the gap between the initial perceived position and the subsequent action position needs to be bridged.

Representational momentum and related types of displacement appear to address exactly this issue: by adjusting the representation of the target to reflect where the target would be in the very near future, the gap between the initial perceived position and the subsequent action position can be (at least partially) bridged. Therefore, representational momentum and related types of displacement allow an observer to make a more adaptive or effective response to the target than might otherwise be possible. Representational momentum and related types of displacement are therefore quite relevant to interceptive behavior; although mechanisms potentially involved in interceptive behavior have been studied in a variety of organisms including humans (e.g., Bootsma & van Wieringen, 1990; Brouwer, Brenner, & Smeets, 2002; McBeath, Shaffer, & Kaiser, 1996; Senot, Prevost, & McIntyre, 2003), dogs (e.g., Shaffer, Krauchunas, Eddy, & McBeath, 2004), dragonflies (e.g., Olberg, Worthington, & Venator, 2000), and bats (e.g., Simmons, Fenton, & O'Farrell, 1979), a compensatory mechanism such as representational momentum has not typically been considered by researchers examining interceptive behaviors. However, researchers examining representational momentum have suggested that displacement can be influenced by the activation of motor action plans regarding the target (e.g., Jordan et al., 2002; Jordan & Knoblich, 2004), and this would be consistent with the notion that displacement plays a useful role in successful interceptive behavior.

Once a response from the observer has reached the target, there is no need for the representation of the target to stay permanently displaced; indeed, a longer-lasting displacement would be maladaptive in that it would lead to a permanent distortion of long-term memory for that target. What might be more useful is a displacement that existed only during the interval in which a brief response would be made, and that then decreased before the distorted information could be encoded into a more permanent long-term storage. Freyd and Johnson (1987) reported the magnitude of representational momentum peaked after a few hundred milliseconds and then declined to zero; however, Jordan et al. (2002) reported that when observers had control over when the target vanished (i.e., when observers had activated motor action plans regarding the target), an initial increase in forward displacement did not occur, but forward displacement decreased with increases in retention interval. Although findings regarding an initial increase in forward displacement are mixed, findings regarding a decrease in displacement with increases in retention interval beyond a few hundred milliseconds are more consistent (although for a possible exception, see Kerzel, 2000). Generally, an initial or early peak followed by a decrease in displacement with increases in retention interval should facilitate an immediate response to the target while preserving the fidelity of a more long-term memory.

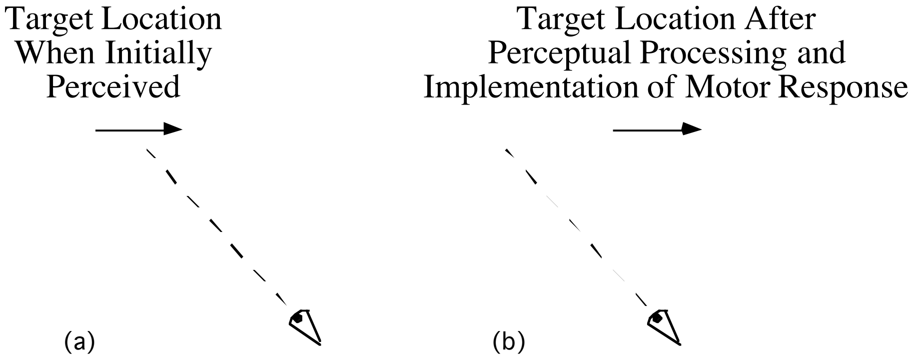

Figure 4. An illustration of the importance of displacement. In panel (a), a moving target is initially sensed, and perceptual and cognitive processing begins. During this time the target continues to move. In panel (b), the initial perceptual and cognitive processing is complete, but the target is no longer at the position where it was initially perceived. In order for a response such as catching, blocking, hitting or intercepting to be maximally effective, an observer must compensate for the movement of the target during the time between when perceptual processing was initiated and when that processing is completed and a motor response initiated, that is, an observers must "bridge the gap" between perception and action. This bridging of the gap might be accomplished by representational momentum and related types of displacement.

The notion that representational momentum and related types of displacement bridge the gap between perception and action is consistent with other views regarding the relationship of perception and action. For example, in recent "forward modeling" approaches, responses to stimuli are coded in terms of their anticipated sensory effects (e.g., Blakemore, 2003; Desmurgent & Grafton, 2003), and such coding would involve precisely the types of information characterized by displacement. Even so, it is not clear if a bridge between perception and action that is based on displacement involves a distinct structure separate from perception pathways and action pathways (e.g., analogous to an interneuron which bridges afferent and efferent pathways) or involves an overlap of perception pathways with action pathways. The possibility of overlap is consistent with Prinz's

(1992, 1997) proposal of a common coding approach to perception and action in which the representations involved in perceiving an action are the same as the representations involved in carrying out that action. Consistent with this, Decety and Grezes (1999) concluded from their review of brain imaging studies that there is a neuronal level common to late products of perception and early antecedents of actions. Such a shared neuronal level is reminiscent of motor theories of perception (e.g., Liberman & Mattingly, 1985), and also suggests the traditional separation of perception and action is overstated or artificial (cf. Johnson-Frey, 2003).

Part IV: Further Bridges

The notions that displacement functions as a bridge between perception and action, and that mental representation incorporates second-order isomorphism between properties of mental representation and properties of the physical world, are related to several additional areas of investigation in contemporary psychophysics and cognitive science. In order to demonstrate the potential breadth and usefulness of these notions, a brief discussion of some of these additional areas of investigation is presented. Of course, many of the areas listed below have previously been postulated to involve mechanisms other than displacement, and the suggestion that displacement contributes to findings in these areas does not mean that displacement is the sole or even primary cause of such findings. Rather, the purpose here is simply to demonstrate potential theoretical applications and interpretations, and to highlight previously unappreciated ways that displacement might contribute to a wide range of perceptual and cognitive phenomena. Furthermore, many of these additional areas of investigation involve the relationship between mental representation and some aspect of the physical world, and so demonstrate new avenues for contemporary psychophysics.

Biases in Spatial Representation

Fröhlich Effect. Just as memory for the final position of a target can be displaced in the direction of target motion, memory for the initial location of a target can be displaced in the direction of target motion. The forward displacement in memory for initial position is referred to as the *Fröhlich effect*, and both the Fröhlich effect (Müsseler & Aschersleben, 1998; Müsseler & Neumann, 1992) and representational momentum (Freyd & Finke, 1985; Hubbard & Bharucha, 1988) increase with increases in target velocity. It could be predicted that forward displacement in memory for the final position of a target results not from representational momentum per se, but rather from a Fröhlich effect and a veridical memory for the length of the trajectory; however, when memory for both the initial position and the final position of a target on a blank background has been measured, memory for initial position usually exhibits a backward displacement (opposite to the Fröhlich effect and referred to as the *Onset Repulsion Effect* by Thornton, 2002; see also Actis-Grosso & Stucchi, 2003; Hubbard & Motes, 2002). Also, the addition of context (e.g., a larger enclosing window, Hubbard & Motes, 2005; a flashed object, Müsseler, Stork, & Kerzel, 2002) influences memory for initial position and memory for final position in complementary ways. Displacement in memory for initial position and displacement in memory for final position might be related, but clarification of these issues awaits further research.

Boundary Extension. If observers are shown a picture of a scene, their subsequent memory for that scene is likely to include details and information that were not actually present within the boundaries of the scene, but that might have been present just beyond the boundaries of the scene (e.g., Intraub, Bender, & Mangels, 1992; Intraub, Gottesman, & Bills, 1998). This has been referred to as *boundary extension*, and has been suggested to result from effects of perceptual schemata (Gottesman & Intraub, 2002). During the initial perception of a scene, information from perceptual schemata is combined with perceptually sampled information. Upon subsequent recall, both types of information are retrieved, but observers do not distinguish between what was actually viewed and the schematic additions. Intraub (2002) suggested boundary extension might help an observer anticipate what might become visible in the next fixation. Thus, both boundary extension and representational momentum might reflect the operation of a more general mechanism that biases representation in ways consistent with past experience; like representational momentum, boundary extension might help bridge the gap between perception and action by allowing an observer to anticipate what will (probably) be seen in the immediate future (Hubbard, 1995b, 1996a; cf. Intraub, 2002). Munger, Owens, and Conway (2005) suggested that even though boundary extension and representational momentum involve prediction, they are separate processes that do not interact.

Flash-lag effect. When a stationary stimulus is briefly flashed at a position that is aligned with a continuously visible moving target, the position of the flashed stimulus seems to lag behind the position of the moving target, and this is referred to as the *flash-lag effect* (for review, see Krekelberg & Lappe, 2001; Nijhawan, 2002). Nijhawan (1994, 2001) suggested the flash-lag effect resulted from an extrapolation of the position of the moving target to compensate for neural processing delays[3], and this notion is consistent with the notion of a similar forward extrapolation in memory for final position (i.e., consistent with representational momentum) to compensate for neural processing delays and help bridge the gap between perception and action. When a stationary stimulus is flashed near the midpoint of a moving target's trajectory, a forward displacement of the position of the moving target (Müsseler et al., 2002), but no significant displacement in memory for the position of the flashed stimulus (Hubbard, 2006a), are observed; this pattern is consistent with the possibility that the flash-lag effect results in part from a forward displacement of the moving target. Also, forward displacement of the final position of a moving target is increased when a stationary stimulus is flashed near the end of that target's trajectory, and Munger and Owens (2004) suggested this might occur because a flash-lag effect increases the size of the perceived gap between the flashed stimulus and moving target, and so observers are more likely to accept probe positions further forward as being the same as the target's final position (but see Hubbard, 2006b).

Motion Capture. When a pattern of stationary flickering dots is superimposed on an apparent surface undergoing apparent motion, those dots are perceived to move in the direction of the apparent surface (e.g., Bressan & Vallortigara, 1993; Ramachandran, 1985). More generally, a stationary stimulus can be misperceived as moving in the same direction as a nearby moving stimulus, and this has been referred to as *motion capture* (e.g., Festa-Martino & Welch, 2001; Murakami, 1999). Hubbard (2006b) presented targets exhibiting implied horizontal motion, and a briefly presented stationary object above or below the final location of the moving target was presented near the conclusion of target motion. Memory for the position of the stationary object was displaced in the direction of target motion, and the magnitude of displacement increased with increases in the velocity of the moving target and with decreases in the distance of the stationary object from the moving target. Several discussions of representational momentum suggest forward displacement is related to an asymmetric spreading of activation in the direction of target motion (e.g., Erlhagen & Jancke, 2004; Hubbard, 1995b; Müsseler et al., 2002), and

---

[3] It should be noted that such an extrapolation is not the only hypothesized explanation for the flash-lag effect. Other explanations include temporal integration of the positions of the moving and flashed objects (e.g., Krekelberg & Lappe, 1999), the time required to shift attention (Baldo & Klein, 1995), and differential delays in the processing of moving targets and the processing of stationary targets (Eagleman & Sejnowski, 2000; Whitney & Murakami, 1998).

displacement of a nearby stationary object is consistent with the hypothesis that spreading activation (i.e., representational momentum) from the moving target to the stationary object influenced the representation of the stationary object. Thus, representational momentum of a moving target could contribute to motion capture of a nearby stationary object.

Time-To-Contact. When an observer approaches (or is approached by) a target or views a target approaching another object, that observer usually underestimates the remaining time-to-contact (e.g., Schiff & Oldak, 1990). Researchers have examined roles of variables such as velocity (Benguigui, Ripoll, & Broderick, 2003), relative size (DeLucia, 1991), and optical dilation of the object and constriction of the optical gap (Bootsma & Oudejans, 1993) in judgments of time-to-contact and interception, but have not considered a possible role for displacement. Gray and Thornton (2001) reported a positive correlation between the magnitude of representational momentum for a target in the picture plane and the magnitude of underestimation of time-to-contact for a target that approached a barrier in the picture plane. Thornton and Hayes (2004) reported that observers who viewed a virtual reality simulation of forward motion exhibited representational momentum for the location of the self. By displacing the represented position of the target or the self forward, representational momentum could reduce the represented distance between the target and observer; this would make it appear as if contact would occur more quickly, and thus contribute to an underestimation of time-to-contact. Such a role for representational momentum in judgments of time-to-contact is consistent with previous suggestions that some time-to-contact tasks involve cognitive clocking or motion extrapolation (cf. DeLucia & Liddell, 1998; Tresilian, 1995).

General Issues in Cognition

Naïve Physics. There have been a number of demonstrations that untutored observers often have inaccurate intuitions regarding the functioning of physical systems. For example, when observers choose from a set of static drawings depicting different paths which path a ball shot out of a spiral tube would follow after exiting the tube, many observers choose a drawing depicting a path that is consistent with a “curvilinear impetus” in which the ball follows a curved trajectory after exiting the tube (e.g., McCloskey & Kohl, 1983; but see Catrambone, Jones, Jonides, & Seifert, 1995; Cooke & Breedin, 1994a,b). When observers predict the trajectory that an object released from a horizontally moving object would follow, many observers exhibit a naïve “straight-down belief” in which a released object would follow a vertical path of descent (McCloskey, Washburn, & Felch, 1983). Similarly, when observers choose from a number of static drawings depicting different paths which path an object moving horizontally past the edge of a surface (e.g., over the edge of a cliff) would follow, or which path would be followed by a weighted pendulum when the string was cut (Caramazza, McCloskey, & Green, 1981), many observers choose a path closer to a straight-down vertical than to the physically correct parabola.

Although numerous studies on naïve physics suggest observers do not have an accurate understanding of physical principles, some theories of representational momentum (or of displacement more generally) suggest observers do (at some level) have an accurate understanding of (at least subjective consequences of) physical principles. How can this apparent contradiction be reconciled? One possibility is that when asked a question about a specific physical system, observers without specific descriptive physical knowledge might be more likely to rely on mental simulation (Schwartz & Black, 1996), and in such a quasi-perceptual mental simulation representational momentum (and other relevant biases) would be exhibited (e.g., a gradually-straightening curved trajectory in the spiral tube task might reflect an averaging of a constant forward representational momentum with a diminishing inward representational centripetal force; see Hubbard, 1996b). Observers with specific descriptive physical knowledge (e.g., from formal instruction in physics) would not need to appeal to such a quasi-perceptual simulation, and would produce an answer based on semantic retrieval. Such a semantic representation need not, of course, exhibit the same properties as would a quasi-perceptual simulation. This is consistent with previous suggestions of dissociation between explicit physical knowledge and the knowledge that underlies displacement (e.g., Freyd & Jones, 1994; Kozhevnikov & Hegarty, 2001).

The choice of a straight-down trajectory for a target released from an elevated horizontally moving source might reflect representational gravity and representational momentum along the vertical axis coupled with a lack of representational momentum along the horizontal axis. If observers are not aware of the horizontal component of the motion of such a falling target (e.g., perhaps because their frame of reference is the moving object from which the target was released and the falling target remains directly below that object), then they would not extrapolate motion along the horizontal axis, and so the target would be represented as moving straight down along a vertical trajectory. Such an explanation is consistent with the idea that representational momentum is strongest along the path that observers believe the target will travel (e.g., Hubbard, 1994), even when that path is a physically incorrect one (e.g., Freyd & Jones, 1994), and is consistent with Kerzel's (2003a) suggestion that attention is necessary for displacement. Displacement might depend upon which part of the display functions as a frame or point of reference, and on the relationship between that frame or point of reference and the target. Such a notion is consistent with the importance of context for displacement noted earlier.

Causal Cognition. Michotte (1946/1963) suggested that observers directly perceive causality. In the launching effect paradigm that Michotte developed, a moving stimulus, referred to here as a *launcher*, contacts a stationary target that subsequently begins to move. Hubbard et al. (2001) reported forward displacement of launched targets was less than forward displacement of nonlaunched control targets, and they suggested this pattern reflected a belief that the launcher imparted impetus to the target. According to naïve impetus theory (McCloskey, 1983), when a moving stimulus contacts a previously stationary target and that target then begins to move, motion of that target is attributed to an impetus imparted from the originally moving stimulus that dissipates with subsequent target motion. If observers attributed motion of a launched target to an impetus imparted from the launcher, then those observers would expect a launched target to stop moving as soon as impetus imparted from the launcher dropped below the level needed to maintain motion. Forward displacement decreases when observers expect a target to stop (Finke, Freyd, & Shyi, 1986), and so displacement of a target in a launching effect display was decreased. Evidence consistent with such an impetus explanation has subsequently been reported in a several studies (Hubbard & Favretto, 2003; Hubbard & Ruppel, 2002; Hubbard, Ruppel, & Courtney, 2005; see also Kozhevnikov & Hegarty, 2001).

The idea that displacement could reflect naïve impetus is consistent with the emphasis on subjective consequences of physical principles noted earlier. When observers view a stationary physical object that begins moving immediately after being pushed by contact from a previously moving physical object, those observers see that pushed object subsequently slow down and stop unless additional pushing is applied. This behavior of a pushed object reflects friction from the surface the object moves across and the medium the object moves through, but rather than mental representation incorporating the objective principle that an object in motion will continue in motion unless acted upon by an outside force and also incorporating the existence of friction as a separate outside force that acts upon a moving object, mental representation just incorporates the simpler impetus idea that an initially stationary object that began moving as a result of receiving a push will slow down and stop unless a compensating force is applied. The resulting idea of impetus could allow reasonably accurate prediction of the behavior of physical objects in a majority of situations likely to be encountered, and so an observer could more easily model the behavior of a target by using a simpler (but incorrect) “impetus” notion than by using a more complex (and correct) “momentum plus friction” notion (for discussion, see Hubbard, 2004).

Perceiving Past Actions. A consideration of representational momentum and related types of displacement highlights the sensitivity of an observer to forces and dynamics currently acting on a target. However, observers might also be sensitive to forces and dynamics that previously acted on a target and left traces of their actions in the shape or structure of that target. Leyton (1989, 1992) and Arnheim (1974, 1988) argued that the appearance or shape of an object often reflects the forces that created or operated on that object (e.g., the winding or twisting shapes of tree trunks, the traces of waves on a beach, and the spiral curve of a snail’s shell all preserve information regarding their creation). Similarly, visual shapes as complex as sculptures and paintings (Arnheim, 1974, 1988) or as simple as handwritten letters (Babcock & Freyd, 1988; Tse & Cavanagh, 2000) contain information that specifies the direction and magnitude of the forces used in the creation of those shapes. More broadly, an observer can “read” the past history of forces that operated on an object (and actions to which that object was exposed) by examining the shape and structural features of that object. Although some previous discussions of perception and action suggest perception is influenced by a potential subsequent action of the individual (e.g., Goodale & Milner, 1992; Milner & Goodale, 1995), it is clear that perception can also be sensitive to previous actions upon or by stimuli.

The extent to which a person is able to perceive or exploit the dynamics involved in the previous creation of a stimulus might depend in part upon whether the person was involved in the creation of that stimulus, and this *authorship effect* has recently been investigated by Knoblich and colleagues. When observers viewed animations of moving dots that recreated the dynamics of previously drawn letters or trajectories, those observers were able to distinguish between animations based on letters or trajectories they had previously produced and animations based on letters or trajectories other people had previously produced (Knoblich & Prinz, 2001) and could distinguish whether a single stroke had been previously drawn in isolation or followed by another stroke (Knoblich, Seigerschmidt, Flach, & Prinz, 2002). Knoblich and colleagues suggest that these results demonstrate that action perception involves a simulation of the action. Thus, a person “reads” the dynamics of a stimulus by activating his or her action representations during perception. There will usually be a better match between one's action representations and the dynamics of a stimulus if that stimulus had been produced by one's own actions, and so a person would be more sensitive to the dynamics of a self-produced stimulus than to the dynamics of an other-produced stimulus. Such an explanation is consistent with the forward modeling approaches and motor theories of perception that were noted earlier.

Structural Dynamics and Shape. There are additional types of dynamics specified by the shape and structure of an object, and perhaps the simplest of these involves "pointing" (e.g., Attneave, 1968; Palmer, 1980; Palmer & Bucher, 1981, 1982). The direction in which a target is perceived to point influences the direction of subsequent apparent motion (McBeath & Morikawa, 1997; McBeath, Morikawa, & Kaiser, 1992); also, memory for a pointing shape can be displaced in the direction of pointing (Freyd & Pantzer, 1995) or toward a smaller angular size (Hubbard & Blessum, 2001). These patterns suggest mental representation is influenced by the dynamics of a pointing shape. The perceived pointing of a triangle along a given axis is enhanced when motion of the triangle occurs along that axis (Bucher & Palmer, 1985), and as noted earlier, forward displacement is increased if a target moves in the direction of pointing (Freyd & Pantzer, 1995; Nagai & Yagi, 2001). It might be that pointing draws attention toward the area in front of the point, and this additional attention results in a larger displacement; such a notion would be consistent with suggestions that displacement requires attention (e.g., Kerzel, 2003a). More generally, perhaps pointing dynamics and motion dynamics sum when motion is in the direction of pointing, but partially cancel when motion is in the direction opposite of pointing.

Aesthetics. A sensitivity to implied dynamics in the shape and structure of a stimulus might contribute to aesthetic experience. Freyd (1992) suggested that memory for the position of a limb in a piece of sculpture or for an object depicted in a painting might be displaced in the direction of any implied dynamic as soon as an observer shifts his or her gaze to another region of the artwork. If the observer then glances back at the initially fixated region, there will be a mismatch between the remembered (displaced) information and the perceptually sampled information. Such a mismatch could produce a violation of expectancies that results in a pleasurable (cf. Meyer, 1956) or arousing (cf. Berlyne, 1971; McMullen, 1982) aesthetic experience. The span of time between when fixation has moved away from a specific region and then returned to that region might be on the order of a few hundred milliseconds, and if displacement existed only for that brief duration, then it could produce a brief aesthetic experience without permanently biasing memory. However, if memory for some part of an aesthetic stimulus was actually displaced in the direction of the implied dynamic, then a subsequent perception of that part of the aesthetic stimulus would appear to be behind the remembered location (i.e., to have moved in the direction opposite to the implied dynamic). Consideration of this led Hubbard and Courtney (in press) to distinguish between memory dynamics and perception dynamics, and to suggest these two different types of dynamics exhibited different properties.

In addition to structural dynamics arising from or within a single shape, structural dynamics can arise from the configuration of objects or from the location of an object within the visual field, and these dynamics might also influence aesthetics. Arnheim (1974) suggested dynamic tension in a work of art arises from configurations that appear “unbalanced.” An example of an unbalanced configuration in a work of art would be a painting that depicted more massive objects in the top half of the picture plane than in the bottom half of the picture plane (Winner, Dion, Rosenblatt, & Gardner, 1987). It might be possible to account for such dynamic tension and lack of balance by a consideration of representational gravity: The asymmetrical direction of gravitational attraction makes it more likely that a target would move downward rather than upward, and the possible range of a potential downward motion would be larger for targets higher in the picture plane than for targets lower in the picture plane. Thus, observers might expect an object higher in the picture plane to fall (or fall farther), whereas observers might not expect an object lower in the picture plane to fall (or fall as far). The expectation that a target higher in the picture plane is more likely to fall (or fall farther) might suggest less equilibrium or stability, and so paintings that contain more massive targets in their top half would therefore appear more unbalanced.

Mental Imagery. Shepard (1984, 1994) argued that many properties of mental representation reflected ecological constraints (but see Hecht, 2001; Kubovy & Epstein, 2001; Schwartz, 2001); however, he focused on visual and geometric aspects of stimuli, and given that invariant physical principles such as momentum are not visual or geometric per se, such dynamics might be less likely to be captured by models of mental imagery that focus on visual and geometric aspects of the stimulus (e.g., Kosslyn, 1980; Shepard, 1981). Finke and Shepard (1986; Finke, 1989) argued that mental images are functionally equivalent to perceptual representations, but whether this equivalence includes dynamic as well as kinematic information is less clear (but see Schwartz, 1999). If dynamic information is included within mental imagery, then functional equivalence could include spatiotemporal properties of representation; perhaps mental images exhibit or incorporate the spatiotemporal coherence that Freyd (1987) speculated to underlie representational momentum. Indeed, evidence consistent with spatiotemporal coherence in mental imagery has been reported: the directional aspect of spatiotemporal coherence is demonstrated in the greater ease in imaging processes in the "natural direction" (e.g., it is more difficult to image the reverse action for sequences such as water pouring from a glass, Schwartz & Black, 1999, or movement of a block and pulley system, Hegarty, 1992), and the continuous aspect of spatiotemporal coherence is demonstrated in the analogue nature of mental imagery (e.g., Shepard, 1981).

The possibility that mental imagery and representational momentum might be related is supported by findings that (a) the axis of target rotation similarly influences performance in mental rotation and in representation momentum (Munger, Solberg, Horrocks, & Preston, 1999), (b) experimental participants who exhibit faster velocities in mental rotation exhibit larger magnitudes of representational momentum (Munger, Solberg, & Horrocks, 1999), (c) the same cortical areas are relatively more activated during mental imagery and during representational momentum (Amorim, Lang, Lindinger, Mayer, Deecke, & Berthoz, 2000), and (d) experimental participants who exhibit higher scores on the Vividness of Visual Imagery Questionnaire exhibit larger magnitudes of representational momentum (Senior, Barnes, & David, 2001). Along these lines, Kelly and Freyd (1987) suggested that representational momentum might reflect an analogue form of representation similar to that underlying mental imagery, and Hubbard (2002) suggested that mental imagery and representational momentum provide convergent evidence that mental representation reflects subjective experience of physical principles. Like representational momentum, mental imagery might exhibit spatiotemporal coherence and also bridge perception and action, and this would be consistent with the idea that mental imagery facilitates perceptual (e.g., Kosslyn, 1994) and motor (e.g., Jeannerod, 1997) processing.

Part V: Summary and Conclusions

Memory for the location of a previously viewed moving target is usually displaced from the actual location of that target. In the absence of physical context (e.g., a landmark or friction surface), cognitive context (e.g., an anticipated change in the direction of target motion), or unusual instructions (e.g., to fixate a location away from a smoothly moving target whose position observers know they will be asked to remember), displacement is usually consistent with the subjective consequences of how invariant physical principles (e.g., momentum) would influence a physical object. Such displacement reflects second-order isomorphism of subjective consequences of physical properties of the world with properties of mental representation. In the presence of cognitive or physical context, the direction and magnitude of displacement is usually consistent with a combination of contributions of both second-order isomorphism and the additional context. As a consequence of displacement, mental representation does not portray the world-as-it-is-right-now, but rather portrays the world-as-it-soon-will-be, or more specifically, the world-as-it-will-be at the time that an immediate response from the observer would reach that target. By temporarily adjusting the representation to reflect how a target would be when an immediate response from the observer would reach that target, displacement helps bridge the gap between perception and action, and thus aids in the spatial localization of stimuli.

Displacement could potentially contribute to a wide range of additional perceptual and cognitive phenomena, and these include other specific biases in spatial processing (e.g., flash-lag effect, motion capture) and more general issues in cognition (e.g., naïve physics, causal cognition). Even if an observer does not respond overtly to a stimulus, displacement in memory for that stimulus could contribute to a covert reaction (e.g., an aesthetic experience). Furthermore, off-line representation such as that involved in mental imagery might reflect the same types of constraints as more on-line perceptual or motor representation; indeed, such a similarity would be expected given the influence of high-level expectations, knowledge, and beliefs on displacement. Patterns of displacement can provide a window into properties of mental representation and into how properties of mental representation relate to properties of the physical world. Although psychophysics has historically been concerned with scaling and with thresholds, a consideration of displacement reveals a new method for examining the relationship between our experience of the world and the properties of the world, and also extends the reach of psychophysics to encompass a wider variety of phenomena and issues. Furthermore, a consideration of the dynamics of mental representation such as representational momentum clearly reveals the wide range of physical, psychophysical, and psychological elements that are relevant to cognitive science.

REFERENCES

Actis-Grosso, R., & Stucchi, N. (2003). Shifting the start: Backward mislocalization of the initial position of a motion. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 675-691.

Amorim, M. A., Lang, W., Lindinger, G., Mayer, D., Deecke, L., & Berthoz, A. (2000). Modulation of spatial orientation by mental imagery: A MEG study of representational momentum. *Journal of Cognitive Neuroscience*, *12*, 569-582.

Arnheim, R. (1974). *Art and visual perception: A psychology of the creative eye (the new version)*. Berkeley, CA: University of California Press.

Arnheim, R. (1988). Visual dynamics. *Scientific American*, *76*, 585-591.

Attneave, F. (1968). Triangles as ambiguous figures. *American Journal of Psychology*, *81*, 447-453.

Babcock, M. K., & Freyd, J. J. (1988). Perception of dynamic information in static handwritten forms. *American Journal of Psychology*, *101*, 111-130.

Baldo, M. V. C., & Klein, S. A. (1995). Extrapolation or attention shift? *Nature*, *378*, 565-566.

Benguigui, N., Ripoll, H., & Broderick, M. P. (2003). Time-to-contact estimation of accelerated stimuli is based on first-order information. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 1083-1101.

Berlyne, D. E. (1971). *Aesthetics and psychobiology*. New York: Appleton-Century-Crofts.

Blakemore, S.-J. (2003). Deluding the motor system. *Consciousness and Cognition*, *12*, 647-655.

Bressan, P., & Vallortigara (1993). What induces capture in motion capture? *Vision Research*, *15*, 2109-2112.

Bootsma, R. J., & Oudejans, R. R. D. (1993). Visual information about time-to-collision between two objects. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1041-1052.

Bootsma, R. J., & van Wieringen, P. C. W. (1990). Timing and attacking forehand drive in table tennis. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 21-29.

Brouwer, A. M., Brenner, E., & Smeets, J. B. J. (2002). Perception of acceleration with a short presentation time: Can acceleration be used in interception? *Perception & Psychophysics*, *64*, 1160-1168.

Brouwer, A. M., Franz, V. H., & Thornton, I. M. (2004). Representational momentum in perception and grasping: Translating versus transforming object. *Journal of Vision*, *4*, 575-584.

Bucher, N. M., & Palmer, S. E. (1985). Effects of motion on perceived pointing of ambiguous triangles. *Perception & Psychophysics*, *38*, 227-236.

Caramazza, A., McCloskey, M., & Green, B. (1981). Naive beliefs in “sophisticated” subjects: Misconceptions about trajectories of objects. *Cognition*, *9*, 117-123.

Catrambone, R., Jones, C. M., Jonides, J., & Seifert, C. (1995). Reasoning about curvilinear motion: Using principles or analogy. *Memory & Cognition*, *23*, 368-373.

Cooke, N. J., & Breedin, S. D. (1994a). Constructing naive theories of motion on the fly. *Memory & Cognition*, *22*, 474-493.

Cooke, N. J., & Breedin, S. D. (1994b). Naive misconceptions of Cooke and Breedin’s research: Response to Ranney. *Memory & Cognition*, *22*, 503-507.

Cooper, L. A. (1975). Mental rotation of random two-dimensional shapes. *Cognitive Psychology*, *7*, 20-43.

Cooper, L. A. (1976). Demonstration of a mental analog of an external rotation. *Perception & Psychophysics*, *19*, 296-302.

Cooper, L. A., & Munger, M. P. (1993). Extrapolations and remembering positions along cognitive trajectories: Uses and limitations of analogies to physical momentum. In N. Eilan, R. McCarthy, & B. Brewer (Eds.), *Spatial representation: Problems in philosophy and psychology* (pp. 112-131). Cambridge, MA: Blackwell.

Decety, J., & Grezes, J. (1999). Neural mechanisms subserving the perception of human actions. *Trends in Cognitive Sciences*, *3*, 172-178.

DeLucia, P. R. (1991). Pictorial depth cues and motion-based information for depth perception. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 738-748.

DeLucia, P. R., & Liddell, G. W. (1998). Cognitive motion extrapolation and cognitive clocking in prediction motion tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 901-914.

Desmurget, M., & Grafton, S. (2003). Feedback or feedforward control: End of a dichotomy. In S. H. Johnson-Frey (Ed.), *Taking action: Cognitive neuroscience perspectives on intentional acts* (pp. 289-338). Cambridge, MA: MIT Press.

Eagleman, D. M., & Sejnowski, T. J. (2000). Motion integration and postdiction in visual awareness. *Science*, *287*, 2036-2038.

Erlhagen, W., & Jancke, D. (2004). The role of action plans and other cognitive factors in motion extrapolation: A modeling study. *Visual Cognition*, *11*, 315-340.

Festa-Martino, E., & Welsh, L. (2001). Motion capture depends upon signal strength. *Perception*, *30*, 489-510.

Finke, R. A. (1989). *Principles of mental imagery*. Cambridge, MA: MIT Press.

Finke, R. A., Freyd, J. J., & Shyi, G. C. W. (1986). Implied velocity and acceleration induce transformations of visual memory. *Journal of Experimental Psychology: General*, *115*, 175-188.

Finke, R. A., & Shepard, R. N. (1986). Visual functions of mental imagery. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance. Vol. 2: Cognitive processes and performance* (pp. 37.1-37.55). New York: Wiley.

Freyd, J. J. (1983). The mental representation of movement when static stimuli are viewed. *Perception & Psychophysics*, *33*, 575-581.

Freyd, J. J. (1987). Dynamic mental representations. *Psychological Review*, *94*, 427-438.

Freyd, J. J. (1992). Dynamic representations guiding adaptive behavior. In F. Macar, V. Pouthas, & W. J. Friedman (eds.). *Time, action, and cognition: Towards bridging the gap* (pp. 309-323). Dordrecht: Kluver Academic Publishers.

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*, 126-132.

Freyd, J. J., & Finke, R. A. (1985). A velocity effect for representational momentum. *Bulletin of the Psychonomic Society*, *23*, 443-446.

Freyd, J. J., & Johnson, J. Q. (1987). Probing the time course of representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 259-269.

Freyd, J. J., & Jones, K. T. (1994). Representational momentum for a spiral path. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*, 968-976.

Freyd, J. J., & Pantzer, T. M. (1995). Static patterns moving in the mind. In S. M. Smith, T. B. Ward, & R. A. Finke (Eds.), *The creative cognition approach* (pp. 181-204). Cambridge, MA: MIT Press.

Freyd, J. J., Pantzer, T. M., & Cheng, J. L. (1988). Representing statics as forces in equilibrium. *Journal of Experimental Psychology: General*, *117*, 395-407.

Futterweit, L. R., & Beilin, H. (1994). Recognition memory for movement in photographs: A developmental study. *Journal of Experimental Child Psychology, 57*, 163-179.

Getzmann, S. (2005). Representational momentum in spatial hearing does not depend on eye movements. *Experimental Brain Research*, *165*, 229-238.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neuroscience*, *15*, 22-25.

Gottesman, C. V., & Intraub, H. (2002). Surface construal and the mental representation of scenes. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 589-599.

Gray, R., & Thornton, I. M. (2001). Exploring the link between time to collision and representational momentum. *Perception*, *30*, 1007-1022.

Hayes, A. E., & Freyd, J. J. (2002). Representational momentum when attention is divided. *Visual Cognition*, *9*, 8-27.

Hecht, H. (2001). Regularities of the physical world and the absence of their internalization. *Behavioral and Brain Sciences*, *24*, 608-617.

Hegarty, M. (1992). Mental animation: Inferring motion from static displays of mechanical systems. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*, 1084-1102.

Hubbard, T. L. (1990). Cognitive representation of linear motion: Possible direction and gravity effects in judged displacement. *Memory & Cognition*, *18*, 299-309.

Hubbard, T. L. (1993). The effects of context on visual representational momentum. *Memory & Cognition, 21,* 103-114.

Hubbard, T. L. (1994). Judged displacement: A modular process? *American Journal of Psychology*, *107*, 359-373.

Hubbard, T. L. (1995a). Cognitive representation of motion: Evidence for representational friction and gravity analogues. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 241-254.

Hubbard, T. L. (1995b). Environmental invariants in the representation of motion: Implied dynamics and representational momentum, gravity, friction, and centripetal force. *Psychonomic Bulletin & Review*, *2*, 322-338.

Hubbard, T. L. (1996a). Displacement in depth: Representational momentum and boundary extension. *Psychological Research/Psychologische Forschung*, *59*, 33-47.

Hubbard, T. L. (1996b). Representational momentum, centripetal force, and curvilinear impetus. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 1049-1060.

Hubbard, T. L. (1997). Target size and displacement along the axis of implied gravitational attraction: Effects of implied weight and evidence of representational gravity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*, 1484-1493.

Hubbard, T. L. (1998a). Representational momentum and other displacements in memory as evidence for nonconscious knowledge of physical principles. In S. R. Hameroff, A. W. Kaszniak & A. C. Scott (Eds.), *Towards a science of consciousness II: The second Tucson discussions and debates* (pp. 505-512). Cambridge, MA: MIT Press.

Hubbard, T. L. (1998b). Some effects of representational friction, target size, and memory averaging on memory for vertically moving targets. *Canadian Journal of Experimental Psychology*, *52*, 44-49.

Hubbard, T. L. (1999). How consequences of physical principles influence mental representation: The environmental invariants hypothesis. In P. R. Killeen & W. R. Uttal (Eds.), *Fechner Day 99: The end of 20th century psychophysics. Proceedings of the 15th Annual Meeting of the International Society for Psychophysics* (pp. 274-279). Tempe, AZ, USA: The International Society for Psychophysics.

Hubbard, T. L. (2001). The effect of height in the picture plane on the forward displacement of ascending and descending targets. *Canadian Journal of Experimental Psychology*, *55*, 325-330.

Hubbard, T. L. (2002). Mental representation reflects subjective experience: Convergent evidence from imagery and representational momentum. *Journal of Mental Imagery*, *26*, 60-65.

Hubbard, T. L. (2004). The perception of causality: Insights from Michotte's launching effect, naive impetus theory, and representational momentum. In A. M. Oliveira, M.P. Teixeira, G. F. Borges, & M. J. Ferro (Eds.), *Fechner Day 2004* (pp. 116-121). Coimbra, Portugal: The International Society for Psychophysics.

Hubbard, T. L. (2006a). Does representational momentum contribute to the flash-lag effect? *Manuscript submitted for publication.*

Hubbard, T. L. (2006b). Representational momentum and motion capture. *Manuscript submitted for publication.*

Hubbard, T. L. (in press-a). Approaches to representational momentum: Theories, models, and controversies. In R. Nijhawan & B. Khurana (Ed.), *Space and time in perception and action*. London, UK: Cambridge University Press.

Hubbard, T. L. (in press-b). Representational momentum and displacement in spatial memory: Findings, theories, and related issues. *Psychonomic Bulletin & Review*.

Hubbard, T. L., & Bharucha, J. J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception & Psychophysics*, *44*, 211-221.

Hubbard, T. L., & Blessum, J. A. (2001). A structural dynamic of form: Displacements in memory for the size of an angle. *Visual Cognition*, *8*, 725-749.

Hubbard, T. L., Blessum, J. A., & Ruppel, S. E. (2001). Representational momentum and Michotte's (1946/1963) "Launching Effect" paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 294-301.

Hubbard, T. L. & Courtney, J. R. (in press). Evidence suggestive of separate visual dynamics in perception and memory. In L. Albertazzi (Ed.), *Visual thought: The depictive space of the mind*. Amsterdam: Benjamins Publishing Company.

Hubbard, T. L., & Favretto, A. (2003). Explorations of Michotte's "Tool Effect;" Evidence from representational momentum. *Psychological Research/Psychologische Forschung*, *67*, 134-152.

Hubbard, T. L., & Motes, M. A. (2002). Does representational momentum reflect a distortion of the length or the endpoint of a trajectory? *Cognition*, *82*, B89-B99.

Hubbard, T. L., & Motes, M. A. (2005). An effect of context on whether memory for initial position exhibits a Fröhlich Effect or an Onset Repulsion Effect. *Quarterly Journal of Experimental Psychology*, *58A*, 961-979.

Hubbard, T. L., & Ruppel, S. E. (1999). Representational momentum and landmark attraction effects. *Canadian Journal of Experimental Psychology*, *53*, 242-256.

Hubbard, T. L., & Ruppel, S. E. (2002) A possible role of naïve impetus in Michotte's "Launching Effect:" Evidence from representational momentum. *Visual Cognition*, *9*, 153-176.

Hubbard, T. L., Ruppel, S. E., & Courtney, J. R. (2005). The force of appearance: Gamma motion, impetus, and representational momentum. *Psicologica*,*26,* 209-228.

Intraub, H. (2002). Anticipatory spatial representation of natural scenes: Momentum without movement? *Visual Cognition*, *9*, 93-119.

Intraub, H., Bender, R. S., & Mangels, J. A. (1992). Looking at pictures but remembering scenes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*, 180-191.

Intraub, H., Gottesman, C. V., & Bills, A. J. (1998). Effects of perceiving and imaging scenes on memory for pictures. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 186-201.

Jeannerod, M. (1997). *The cognitive neuroscience of action*. Cambridge, MA: MIT Press/Blackwell.

Johnson-Frey, S. H. (Ed.). *Taking action: Cognitive neuroscience perspectives on intentional acts*. Cambridge, MA: MIT Press.

Johnston, H., & Jones, M. R. (in press). Higher-order pattern structure influences auditory representational momentum. *Journal of Experimental Psychology: Human Perception and Performance.*

Jordan, J. S., & Knoblich, G, (2004). Spatial perception and control. *Psychonomic Bulletin & Review*, *11*, 54-59.

Jordan, J. S., Stork, S., Knuf, L., Kerzel, D., & Müsseler, J. (2002). Action planning affects spatial localization. In W. Prinz & B. Hommel (eds.), *Attention and performance XIX: Common mechanisms in perception and action* (pp. 158-176). New York: Oxford University Press.

Kelly, M. H., & Freyd, J. J. (1987). Explorations of representational momentum. *Cognitive Psychology*, *19*, 369-401.

Kerzel, D. (2000). Eye movements and visible persistence explain the mislocalization of the final position of a moving target. *Vision Research*, *40*, 3703-3715.

Kerzel, D. (2002a). A matter of design: No representational momentum without predictability. *Visual Cognition*, *9*, 66-80.

Kerzel, D. (2002b). Attention shifts and memory averaging. *Quarterly Journal of Experimental Psychology*, *55*(A), 425-443.

Kerzel, D. (2002c). The locus of "memory displacement" is at least partially perceptual: Effects of velocity, expectation, friction, memory averaging, and weight. *Perception & Psychophysics*, *64*, 680-692.

Kerzel, D. (2003a). Attention maintains mental extrapolation of target position: Irrelevant distractors eliminate forward displacement after implied motion. *Cognition*, *88*, 109-131.

Kerzel, D. (2003b). Centripetal force draws the eyes, not memory of the target, toward the center. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 458-466.

Kerzel, D., Jordan, J. S., & Müsseler, J. (2001). The role of perception in the mislocalization of the final position of a moving target. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 829-840.

Kosslyn, S. M. (1980). *Image and mind*. Cambridge, MA: Harvard University Press.

Kosslyn, S. M. (1994). *Image and brain*. Cambridge, MA: MIT Press.

Kozhevnikov, M., & Hegarty, M. (2001). Impetus beliefs as default heuristics: Dissociation between explicit and implicit knowledge about motion. *Psychonomic Bulletin & Review*, *8*, 439-453.

Knoblich, G. & Prinz, W. (2001). Recognition of self-generated actions from kinematic displays of drawing. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 456-465.

Knoblich, G., Seigerschmidt, E., Flach, R., & Prinz, W. (2002). Authorship effects in the prediction of handwriting strokes: Evidence for action simulation during action perception. *Quarterly Journal of Experimental Psychology*, *55*(A), 1027-1046.

Krekelberg, B., & Lappe, M. (1999). Temporal recruitment along the trajectory of moving objects and the perception of motion. *Vision Research*, *39*, 2669-2679.

Krekelberg, B. & Lappe, M. (2001). Neuronal latencies and the position of moving objects. *Trends in Neurosciences*, *24*, 335-339.

Kubovy, M., & Epstein, W. (2001). Internalization: A metaphor we can live without. *Behavioral and Brain Sciences*, *24*, 618-625.

Leyton, M. (1989). Inferring causal history from shape. *Cognitive Science*, *13*, 357-387.

Leyton, M. (1992). *Symmetry, causality, mind.* Cambridge, MA: MIT Press.

Liberman, A. M., & Mattingly, I. G. (1985). The motor theory of speech perception revised. *Cognition*, *21*, 1-36.

McBeath, M. K., & Morikawa, K. (1997). Forward-facing motion biases for rigid and nonrigid biologically likely transformations. *Perceptual and Motor Skills*, *85*, 1187-1193.

McBeath, M. K., Morikawa, K., & Kaiser, M. K. (1992). Perceptual bias for forward-facing motion. *Psychological Science*, *3*, 362-367.

McBeath, M. K., Shaffer, D. M., & Kaiser, M. K. (1996). On catching fly balls. *Science*, *273*, 258-260.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 299-324). Hillsdale, NJ: Erlbaum.

McCloskey, M., & Kohl, D. (1983). Naive physics: The curvilinear impetus principle and its role in interactions with moving objects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*, 146-156.

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive physics: The straight-down belief and its origin. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*, 636-649.

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience*, *4*, 693-694.

McMullen, P. T. (1982). Connative responses to musical stimuli: A theoretical explanation. *Council for Research in Music Education*, *7*, 45-57.

Meyer, L. B. (1956). *Emotion and meaning in music*. Chicago: The University of Chicago Press.

Michotte, A. (1963). *The perception of causality* (T. R. Miles & E. Miles, Trans.). New York: Basic Books (original work published 1946).

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. New York: Oxford University Press.

Munger, M. P., & Owens, T. R. (2004). Representational momentum and the flash-lag effect. *Visual Cognition*, *11*, 81-103.

Munger, M. P., Owens, T. R., & Conway, J. E. (2005). Are boundary extension and representational momentum related? *Visual Cognition*, 12, 1041-1056.

Munger, M. P., Solberg, J. L., & Horrocks, K. K. (1999). On the relation between mental rotation and representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 1557-1568.

Munger, M. P., Solberg, J. L., Horrocks, K. K., & Preston, A. S. (1999). Representational momentum for rotations in depth: Effects of shading and axis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 157-171.

Murakami, I. (1999). Motion-transparent inducers have different effects of induced motion and motion capture. *Vision Research*, *39*, 1671-1681.

Müsseler, J., & Aschersleben, G. (1998). Localizing the first position of a moving stimulus: The Fröhlich effect and an attention-shifting explanation, *Perception & Psychophysics*, *60*, 683-695.

Müsseler, J., & Neumann, O. (1992). Apparent distance reduction with moving stimuli (tandem effect): Evidence for an attention-shifting model. *Psychologische Forshung/Psychological Research*, *54*, 246-266.

Müsseler, J., Stork, S., & Kerzel, D. (2002). Comparing mislocalizations with moving stimuli: The Fröhlich effect, the flash-lag, and representational momentum. *Visual Cognition*, *9*, 120-138.

Nagai, M., Kazai, K., & Yagi, A. (2002). Larger forward memory shift in the direction of gravity. *Visual Cognition*, *9*, 28-40.

Nagai, M., & Yagi, A. (2001). The pointedness effect on representational momentum. *Memory & Cognition*, *29*, 91-99.

Nijhawan, R. (1994). Motion extrapolation in catching. *Nature*, *370*, 256-257.

Nijhawan, R. (2001). The flash-lag phenomenon: Object motion and eye movements. *Perception*, *30*, 263-282.

Nijhawan, R. (2002). Neural delays, visual motion and flash-lag effect. *Trends in Cognitive Sciences*, *6*, 387-393.

Olberg, R. M., Worthington, A. H., & Venator, K. R. (2000). Prey pursuit and interception in dragonflies. *Journal of Comparative Physiology A*, *186*, 155-162.

Palmer, S. E. (1980). What makes triangles point: Local and global effects in configurations of ambiguous triangles. *Cognitive Psychology*, *12*, 285-305.

Palmer, S. E., & Bucher, N. M. (1981). Configural effects in perceived pointing of ambiguous triangles. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 88-114.

Palmer, S. E., & Bucher, N. M. (1982). Textural effects in perceived pointing of ambiguous triangles. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 693-708.

Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology*, *4*, 1-20.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, *9*, 129-154.

Ramachandran, V. S. (1985). Apparent motion of subjective surfaces. *Perception, 14,* 127-134.

Reed, C. L., & Vinson, N. G. (1996). Conceptual effects on representational momentum. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 839-850.

Schiff, W., & Oldak, R. (1990). Accuracy of judging time to arrival: Effects of modality, trajectory, and gender. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 303-316.

Schwartz, D. L. (1999). Physical imagery: Kinematic versus dynamic models. *Cognitive Psychology*, *38*, 433-464.

Schwartz, R. (2001). Evolutionary internalized regularities. *Behavioral and Brain Sciences*, *24*, 626-628.

Schwartz, D. L., & Black, J. B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science*, *20*, 457-497.

Schwartz, D. L., & Black, T. (1999). Inferences through imagined actions: Knowing by simulated doing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 116-136.

Senior, C., Barnes, J., & David, A. S. (2001). Mental imagery increases representational momentum: Preliminary findings. *Journal of Mental Imagery*, *25*, 177-184.

Senot, P., Prevost, P., & McIntyre, J. (2003). Estimating time to contact and impact velocity when catching an accelerating object with the hand. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 219-237.

Shaffer, D. M., Krauchunas, S. M., Eddy, M., & McBeath, M. K. (2004). How dogs navigate to catch frisbees. *Psychological Science*, *15*, 437-441.

Shepard, R. N. (1975). Form, formation, and transformation of internal representations. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola Symposium* (pp. 87-122). Hillsdale, NJ: Erlbaum.

Shepard, R. N. (1981). Psychophysical complementarity. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual organization* (pp. 279-341). Hillsdale, NJ: Erlbaum.

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imaging, thinking, and dreaming. *Psychological Review*, *91*, 417-447.

Shepard, R. N. (1994). Perceptual-cognitive universals as reflections of the world. *Psychonomic Bulletin & Review*, *1*, 2-28.

Shepard, R. N., & Cooper, L. A. (1982). *Mental images and their transformations*. Cambridge, MA: MIT Press.

Shepard, R. N., & Chipman, S. (1970). Second-order isomorphism of internal representations: Shapes of states. *Cognitive Psychology*, *1*, 1-17.

Simmons, J. A., Fenton, M. B., & O'Farrell, M. J. O. (1979). Echolocation and the pursuit of prey by bats. *Science*, *203*, 16-21.

Thornton, I. M. (2002). The onset repulsion effect. *Spatial Vision*, *15*, 219-243.

Thornton, I. M., & Hayes, A. E. (2004). Anticipating action in complex scenes. *Visual Cognition*, *11*, 341-370.

Thornton, I. M., & Hubbard, T. L. (Eds.). (2002). *Representational momentum: New findings, new directions*. New York: Psychology Press/Taylor & Francis.

Tresilian, J. R. (1995). Perceptual and cognitive processes in time-to-contact estimation: Analysis of prediction-motion and relative judgment tasks. *Perception & Psychophysics*, *57*, 231-245.

Tse, P. U., & Cavanagh, P. (2000). Chinese and Americans see opposite apparent motions in a Chinese character. *Cognition*, *74*, B27-B32.

Verfaillie, K., & d'Ydewalle, G. (1991). Representational momentum and event course anticipation in the perception of implied periodical motions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*, 302-313.

Vinson, N. G., & Reed, C. L. (2002). Sources of object-specific effects in representational momentum. *Visual Cognition*, *9*, 41-65.

Whitney, D., & Murakami, I. (1998). Latency difference, not spatial extrapolation. *Nature Neuroscience*, *1*, 656-657.

Winner, E., Dion, J., Rosenblatt, E., & Gardner, H. (1987). Do lateral or vertical reversals affect balance in paintings? *Visual Arts Research*, *13*, 1-9.

(Manuscript received: 28 June 2004; accepted: 18 January 2005)