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Approaches to representational momentum: theories and models

TIMOTHY L. HUBBARD

Summary

Memory for the final position of a target is usually displaced in the direction of target motion, a finding referred to as *representational momentum*. There are several different approaches to explaining representational momentum, and these approaches range from low-level perceptual mechanisms (e.g., oculomotor behavior) to high-level cognitive mechanisms (e.g., internalization of the effects of momentum). These approaches are overviewed, and a classification system involving internalization theories, belief-based theories, neointernalization theories, low-level theories, and network models is proposed. The extent to which each approach is consistent with the wide range of existent empirical data regarding representational momentum is noted, and possible directions of and considerations for a more unified theory of displacement are addressed.

Memory for the final position of a previously viewed target is often displaced in the direction of target motion. This forward displacement has been referred to as *representational momentum* (Freyd & Finke 1984) and is influenced by numerous variables (Hubbard 1995b, 2005). Although initial studies of representational momentum appeared consistent with the hypothesis that observers internalize or incorporate the principle of momentum into the representation of the target, subsequent studies reported displacement inconsistent with such a literal internalization or incorporation of momentum. For example, variables other than implied momentum such as conceptual knowledge about target identity (Reed & Vinson 1996), expectations regarding future target motion (Verfaillie & d'Ydewalle 1991; Johnston & Jones 2006), attributions about the source of target motion (Hubbard & Ruppel 2002; Hubbard & Favretto 2003), and whether observers visually track the target (Kerzel 2000; Kerzel et al. 2001) influence displacement. Displacement also occurs in the direction opposite to motion (Brehaut & Tipper 1996), along the axis orthogonal to motion (Hubbard & Bharucha 1988), and for stationary objects (Freyd et al. 1988). Any comprehensive approach to representational momentum needs to address this range of findings.

This chapter examines varied approaches to representational momentum, and several theories and models are discussed. Section 20.1 focuses on the definition of representational momentum and provides a brief overview of stimulus presentation, response collection, and empirical findings in studies of representational momentum. It is not an exhaustive review,

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but rather is intended to provide background information (see more detailed review in Hubbard 2005). Section 20.2 provides descriptions of theories and models of representational momentum and displacement, introduces an organizational scheme for categorizing these theories and models, and notes whether each of the theories and models is consistent with, inconsistent with, or does not address the findings in Section 20.1. Section 20.3 considers the possibility of a more complete or unified theory of displacement and suggests considerations for a future theory of representational momentum and displacement. Section 20.4 provides a brief summary.

20.1 A brief overview of representational momentum

In order to understand theories and models discussed in Section 20.2, it is useful to define representational momentum, and then briefly review the methodologies and empirical findings from studies on representational momentum and related types of displacement.

20.1.1 Defining representational momentum

Momentum of a physical object is equal to the product of that object's mass and velocity (i.e., momentum = mass $*$ velocity), and so representational momentum of a given target would presumably reflect the mental representation of the mass and velocity of that target. However, many researchers have used "representational momentum" in a broader sense to refer to any displacement in the remembered position of a previously viewed object that is in the direction of motion (or even any displacement in remembered position more generally). Hubbard (1995b, 2005) urged that "representational momentum" be used in a narrower sense to refer only to the component of displacement that reflected implied momentum, but such a narrower usage has not been uniformly adopted (e.g., see Thornton & Hayes 2004). The term "representational momentum" has also been used to describe both the pattern of displacement and a hypothesized explanatory mechanism for displacement. Although which meaning is intended is usually clear from the context, this dual usage can at times lead to confusion.

20.1.2 Methodology

In the representational momentum literature, stimuli can be presented in any of several different formats, and responses can be collected with any of several different measures. Even so, almost all studies of representational momentum involve computer-driven generation or presentation of stimuli and computer-assisted collection of responses using keyboard presses, cursor positioning and mouse clicks, or touching a computer monitor.

20.1.2.1 Stimulus presentation

Freyd and Finke (1984) presented observers with a small set of discrete concentric rectangular stimuli (inducing stimuli) that implied clockwise or counterclockwise rotation (see

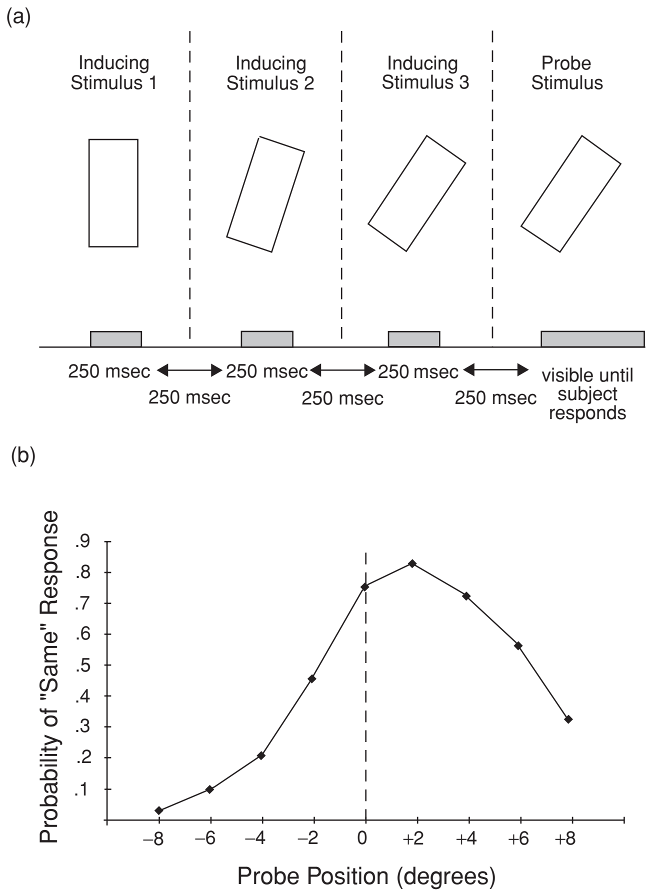

Fig. 20.1 The experimental methodology and results from Freyd and Finke (1984). (a) illustrates a typical trial in which three inducing stimuli and a probe are presented. (b) illustrates the probability of a *same* response as a function of probe orientation relative to the final inducing stimulus. The 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.

top of Fig. 20.1). Hubbard and Bharucha (1988) presented observers with targets that exhibited continuous horizontal or vertical motion and vanished without warning.[1] Implied motion and continuous motion are the most common methods of stimulus presentation, but

[1] Motion depicted in computer-generated animation is never actually "continuous" or "smooth," as computer-generated motion involves discrete presentation of a target at one location followed by a redrawing of that target at a nearby location. However, if the separate presentations occur quickly enough, continuous and smooth motion is perceived. When researchers on representational momentum speak of "continuous" or "smooth" motion, they refer to displays in which differences between successive presentations are not perceivable, and so a target appears to exhibit continuous and smooth motion.

other methods have also been used. Freyd (1983) presented observers with single frozen-action photographs drawn from longer motion sequences (e.g., a person in mid-jump). In variations of this method, Freyd et al. (1988) presented drawings of stimuli that portrayed physical forces in equilibrium (e.g., a weight on a spring), and Hubbard and Courtney (2006) presented drawings of a dynamic figure (i.e., the T'ai-chi tu [yin-yang] symbol). In most studies, observers passively viewed targets, but Jordan and Knoblich (2004) gave observers partial control over direction and velocity of targets, and Jordan et al. (2002) gave observers partial control over when targets vanished.

20.1.2.2 Response collection

Freyd and Finke (1984) presented a probe stimulus after the final inducing stimulus vanished, and observers judged whether the probe was at the same position as the final inducing stimulus or at a different position. Over trials, the probe was slightly in front of, at the same position as, or slightly behind the actual position of the final inducing stimulus. The distribution of probe responses provides an estimate of displacement (see bottom of Fig. 20.1), and this typically involves calculation of either (a) the peak of a quadratic regression (e.g., Freyd & Johnson 1987), (b) the weighted mean (e.g., Munger, Solberg, Horrocks et al. 1999), or (c) the point of subjective equality (e.g., Kerzel 2003c). Probe judgment is the most common response method, but other methods have also been used. A more direct method of measuring displacement introduced by Hubbard and Bharucha (1988) involved observers using a computer mouse to place a cursor at the display coordinates where a target was judged to have vanished, and the difference between the judged vanishing point and the actual vanishing point provided a measure of displacement. More recently, researchers measured displacement using reaching responses in which observers touched the display at the coordinates at which a target was judged to have vanished (e.g., Kerzel & Gegenfurtner 2003; Motes et al. 2008).

20.1.3 Empirical findings

A wide range of variables influences representational momentum and related types of displacement, and Hubbard (2005) classified these variables as characteristics of the target, display, context, or observer.

20.1.3.1 Characteristics of the target

Forward displacement is usually greater with faster target velocities (Freyd & Finke 1985; Hubbard & Bharucha 1988), and accelerating targets exhibit greater forward displacement than do decelerating targets, even when final velocity is constant (Finke et al. 1986). When target motion occurs in the picture plane, forward displacement is greater for horizontal motion than for vertical motion (Hubbard & Bharucha 1988). Descending motion yields greater forward displacement than does ascending motion (Hubbard 1990; Munger & Owens 2004), but differences in forward displacement between leftward motion and rightward motion are not consistently observed (cf. Halpern & Kelly 1993; Hubbard & Bharucha

1988). Conceptual knowledge regarding target identity influences forward displacement (e.g., an upward moving stimulus labeled “rocket” exhibits greater forward displacement than does an otherwise identical stimulus labeled “cathedral,” Reed & Vinson 1996; also Vinson & Reed 2002). The size or implied mass of the target does not influence forward displacement in the direction of motion (Cooper & Munger 1993), but larger targets exhibit greater downward displacement along the axis aligned with implied gravitational attraction regardless of the direction of target motion (Hubbard 1997). Forward displacement is observed for simultaneous multiple targets, even when each target moves in a different direction (Finke & Freyd 1985). Although most studies of forward displacement present visual stimuli, forward displacement has also been found with auditory (Freyd et al. 1990; Getzmann et al. 2004; Johnston & Jones 2006) and tactile (Brouwer et al. 2004) stimuli.

20.1.3.2 Characteristics of the display

If targets rotate in the picture plane, implied motion and continuous motion result in equal forward displacement (Munger & Owens 2004), whereas if targets translate in the picture plane, implied motion results in smaller (Faust 1990) or greater (Kerzel 2003c) forward displacement than does continuous motion. Effects of acceleration and deceleration of the target are greater with continuous motion than with implied motion (Poljansek 2002). Some investigators find forward displacement increases during the first few hundred milliseconds of the retention interval and then decreases with further increases in retention interval (e.g., Freyd & Johnson 1987), but only when target motion is highly predictable (e.g., Kerzel 2002a). Other investigators find an increase and asymptote in forward displacement with increases in retention interval (e.g., Kerzel 2000) or no effect of retention interval (e.g., Halpern & Kelly 1993) on forward displacement. Greater forward displacement is observed with motor responses such as reaching than with perceptual responses such as probe judgment (Kerzel 2003c; Kerzel & Gegenfurtner 2003).

20.1.3.3 Characteristics of the context

Forward displacement increases when a nearby or surrounding stimulus moves in the same direction as the target, and decreases when a nearby or surrounding stimulus moves in the direction opposite to the target (Hubbard 1993b; Whitney & Cavanagh 2002). Forward displacement increases if the target moves toward a landmark and decreases if the target moves away from a landmark (Hubbard & Ruppel 1999). Displacement also occurs along the axis orthogonal to target motion if that orthogonal axis is toward a landmark or other stimulus (Hubbard 1998b; Hubbard & Ruppel 1999) or is aligned with implied gravitational attraction (Hubbard 1990, 1997). If a nontarget stimulus is flashed near the end of target motion, forward displacement increases (Munger & Owens 2004), but if a nontarget stimulus is flashed during the retention interval between when the target vanished and a probe subsequently appeared, forward displacement decreases (Kerzel 2002b). Forward displacement is influenced by whether observers expect a target to change direction (Verfaillie & d’Ydewalle 1991; Hubbard 1994; Johnston & Jones 2006) and whether the final target location corresponds to a good or schematic ending (Hubbard 1993a; Kelly & Freyd 1987).

Forward displacement decreases if the target is initially stationary and subsequent motion of the target is attributed to impetus imparted from a moving stimulus that contacts the target and then launches that target into motion (Hubbard et al. 2001; Hubbard 2004).

20.1.3.4 Characteristics of the observer

Forward displacement increases when attention is divided between the target and another stimulus or task (Hayes & Freyd 2002; Joordens et al. 2004) and decreases when attention to the target is disrupted by presentation of a distractor during the retention interval (Kerzel 2003a). Forward displacement decreases but is not eliminated when the final location of the target is cued prior to when the target vanishes or during the retention interval (Hubbard et al. 2009) or when observers receive explicit instructions regarding representational momentum and are asked to compensate for its effects (Courtney & Hubbard 2008). Whether an observer tracks the target or fixates a stationary point away from the target influences forward displacement for continuously moving targets but not for implied motion targets (Kerzel 2000, 2003a; Kerzel et al. 2001). Forward displacement is influenced by activation of action plans (Jordan et al. 2002; Jordan & Knoblich 2004; Jordan & Hunsinger 2008), but is not influenced by whether observers receive feedback regarding the accuracy of their judgments of target position (Ruppel et al. 2009). Forward displacement is greater in younger children than in adults (Hubbard et al. 1999), but does not differ between older children and adults (Futterweit & Beilin 1994). Individuals with mental retardation exhibit smaller forward displacement (Jarrett et al. 2002), and individuals diagnosed with schizophrenia exhibit a trend for greater forward displacement (Conners et al. 1998) than do matched controls.

20.2 Theories and models of representational momentum

There are several theories and models of representational momentum (and of displacement more generally). Some address general properties of mental representation (e.g., Freyd 1987; Hubbard 2006a), whereas others address displacement for a specific stimulus type (e.g., continuous motion; Kerzel 2000), response measure (e.g., probe judgment; Bertamini 2002), or direction (e.g., forward; Kozhevnikov & Hegarty 2001). They can be grouped into five categories: (a) internalization theories, (b) belief-based theories, (c) neointernalization theories, (d) low-level theories, and (e) network models. The presentation here is necessarily brief and nonexhaustive, and general consistencies and inconsistencies of each theory and model with empirical findings noted in Section 20.1 are summarized in Table 20.1.

20.2.1 Internalization theories

Internalization theories suggest representational momentum results from properties of mental representation. The momentum metaphor is a specific theory regarding displacement in the direction of target motion, and spatiotemporal coherence is a general theory in which representational momentum is linked to changes in mental representation that result from

Table 20.1 *How well different theories of displacement account for the data*

	Theories of Displacement											
	INT		BB			N-INT		LL		NET		
	MM	SC	EE	IK	NI	SOI	AC	OB	MA	VA	EJ	BW
Target												
Velocity	+	+	+	+	+	+	+	+	+	+	+	+
Motion Direction	–	–	?	?	?	?	?	–	–	?	?	?
Orthogonal Direction	–	?	?	+	–	+	+	–	–	+	+	?
Identity	–	–	?	+	?	?	?	?	?	+	+	+
Multiple Targets	+	+	+	+	+	+	+	–	+	+	+	+
Mass/Size	–	?	?	?	–	+	+	?	?	+	?	?
Modality	+	+	+	+	?	+	+	–	?	+	+	+
Display												
Implied Motion	+	+	–	+	+	+	+	–	+	+	+	+
Continuous Motion	+	+	?	+	+	+	+	+	+	+	+	+
Frozen-action Photographs	+	+	–	+	+	+	+	–	–	+	+	+
Retention Interval	+	+	?	?	–	+	+	?	?	+	+	+
Cursor Positioning	+	+	?	+	+	+	+	+	–	+	+	+
Probe Judgment	+	+	–	+	+	+	+	+	+	+	+	+
Reaching	+	+	+	+	+	+	+	+	+	+	+	+
Context												
Surrounding Context	–	–	?	?	–	+	+	?	–	+	+	?
Landmarks	–	–	?	?	–	+	+	?	–	+	+	?
Future Motion	–	–	–	+	+	+	+	?	–	+	+	?
Schematic/ Good Ending	–	?	+	+	+	+	+	?	–	+	+	?
Attribution of Motion Source	–	–	?	+	+	+	+	?	–	+	?	?

Table 20.1 (*cont.*)

	Theories of Displacement											
	INT		BB			N-INT		LL		NET		
	MM	SC	EE	IK	NI	SOI	AC	OB	MA	VA	EJ	BW
Observer												
Allocation of Attention	–	?	?	?	?	?	?	+	+	+	+	+
Knowledge of RM/Feedback	?	?	–	?	?	?	?	?	–	?	?	?
Visual Tracking	–	?	?	–	–	?	?	+	+	?	?	?
Action Plans	–	?	?	?	?	?	+	+	–	+	+	?
Dissociation with Naive Physics	?	?	–	–	–	?	?	?	–	?	?	?
Age	?	?	?	?	?	?	?	?	?	?	?	?
Pathology	?	?	?	?	?	?	?	?	?	?	?	?

Note: A plus sign indicates data are consistent with or support a theory or model, a minus sign indicates data are inconsistent with or do not support a theory or model, and a question mark indicates data do not clearly address a theory or model. INT = internalization theories, BB = belief-based theories, N-INT = neointernalization theories, LL = low-level theories, NET = network models, MM = momentum metaphor, SC = spatiotemporal coherence, EE = explicit extrapolation, IK = implicit knowledge, NI = naive impetus, SOI = second-order isomorphism, AC = anticipatory consciousness, OB = oculomotor behavior, MA = motion aftereffect/perceptual adaptation, VA = vector addition, EJ = Erlhagen/Jancke model, BW = bow-wave model.

dynamic aspects of mental representation. Internalization theories were the earliest and most extensively discussed theories of displacement.

20.2.1.1 Momentum metaphor

The momentum metaphor suggested that the principle of momentum was incorporated into mental representations (Freyd & Finke 1984). As a consequence, mental representations exhibited a type of inertia. Just as a moving physical object cannot be immediately halted because of its momentum, so too a mental representation of that motion cannot be immediately halted because of an analogous momentum within the representational system (Finke & Freyd 1985; Finke et al. 1986). Finke et al. (1986) suggested the internalized form of momentum was relatively abstract, and so representational momentum could potentially accompany changes in stimuli that had no simple analogue to physical motion (e.g., changes in sound, size, color) if such changes could be extrapolated into the future; furthermore, such extrapolation could help observers (a) anticipate future positions of objects that move in a consistent manner, (b) regulate and control body movements, and (c) recognize objects moving to expected or familiar positions. Freyd et al. (1990) speculated representational momentum might have originated in the visual system as an internalization of momentum, but was "confiscated" by other neural systems to aid prediction of the future course of perceived events more generally. Although initially framed as an abstraction of change, the momentum metaphor has often been portrayed as a concrete internalization of physical momentum.

20.2.1.2 Spatiotemporal coherence

Freyd (1987, 1993) suggested representational momentum reflected spatiotemporal coherence between the represented and representing worlds (i.e., between the external physical world and the internal mental representation). Spatiotemporal coherence requires mental representation to be dynamic, and it is this dynamism that results in displacement. In order to be dynamic, a representation must intrinsically and necessarily include or incorporate time. An intrinsic inclusion or incorporation of time entails that the representation exhibits the same constraints as time; in other words, the representation of time must be directional and continuous. A necessary inclusion or incorporation of time requires that temporal aspects of represented information be an integral part of the representation and not a quality (or tag) distinct from a static and unchanging representation (i.e., the representation would need to systematically change over time). By displacing memory in the direction of target motion, and by exhibiting effects of retention interval, representational momentum reflects the directional and continuous aspects of dynamism, respectively. The necessary component of dynamism is reflected in findings that displacement of some sort occurs even if the magnitude and direction of displacement are influenced by observers' expectations or other knowledge (see also Finke & Freyd 1989).

Basing representational momentum on a broad conception of spatiotemporal coherence between the external physical world and the internal mental representation predicts that representational momentum should be found for any stimulus dimension that affords continuous change (Freyd 1992, 1993). This broad notion of spatiotemporal coherence was challenged by Brehaut and Tipper's (1996) finding that memory for the final luminance of inducing stimuli that increased or decreased in luminance was displaced backward toward an average of the inducing stimuli. Given that luminance is a perceptually continuous dimension, a broad spatiotemporal coherence notion predicts that forward displacement should have been exhibited. Brehaut and Tipper suggested representational momentum was limited to dimensions in which change entails motion, rather than being a general aspect of memory for any dimension that affords continuous change. Also, Hubbard (1999, 2006a) suggested spatiotemporal coherence reflected subjective aspects of physical principles rather than objective principles (as displacement reflects subjective experience of mass as weight, Hubbard 1997) and included effects of invariant physical principles in addition to momentum (e.g., gravity).

20.2.2 Belief-based theories

Belief-based theories suggest displacement results from beliefs regarding physical systems and objects in motion. A theory based on explicit extrapolation is a specific theory addressing displacement arising from implied motion, a theory based on implicit knowledge is a general theory, and a theory based on naive impetus is a specific theory focusing on aspects of forward displacement more consistent with notions of naive impetus than with the veridical understanding of momentum.

20.2.2.1 Explicit extrapolation

When discrete inducing stimuli are used to imply motion, it is possible that forward displacement results not from distortion in memory for the final inducing stimulus, but from observers predicting the position of a subsequent inducing stimulus. Finke and Freyd (1985) presented inducing stimuli consisting of patterns of dots in which each dot moved in a different direction. There was one forward probe (the configuration that would have occurred had the inducing stimuli continued) and one backward probe (the configuration identical to the previous [penultimate] inducing stimulus). A probe in which the configuration was the same as the final inducing stimulus was also presented. No difference in error rates or response times to forward probes and backward probes was exhibited, and there was no evidence of displacement. Finke and Freyd (1985) suggested this pattern demonstrated (a) observers in previous experiments were not predicting the position of a subsequent inducing stimuli, and (b) displacement in memory for final position did not result from masking of the final inducing stimulus by the probe or from observers confusing the final inducing stimulus with a previous inducing stimulus.

Finke and Shyi (1988) presented inducing stimuli similar to those in Finke and Freyd (1985). In a memory task, probes were clustered around the configuration of the final inducing stimulus, and forward displacement occurred. In an extrapolation task, probes were clustered around the configuration corresponding to the next configuration of inducing stimuli had the sequence of inducing stimuli continued, and marginally significant backward displacement occurred. Similar differences between displacement in a memory task and displacement in an extrapolation task (when three-dimensional renderings of three-armed figures exhibited apparent rotation), as well as increases in backward displacement in the extrapolation task with increases in target velocity, were reported by Munger and Minchew (2002). Furthermore, it was found that backward displacement in the extrapolation task increased with increases in target velocity. Given that the pattern of displacement in an extrapolation task differs from the pattern of displacement in a memory task, an account of displacement in memory for the final position of a target that is based on explicit prediction of the position of the next inducing stimulus can be rejected.

20.2.2.2 Implicit knowledge of physical principles

Hubbard (1998a) suggested representational momentum and related forms of displacement reflected implicit knowledge of physical principles. Because this knowledge is implicit, it is not available to explicit processes used in paper and pencil tests of physical knowledge (e.g., as in McCloskey & Kohl 1983), but might be available if observers judged veridicality of animated (i.e., dynamic) displays (e.g., as in Kaiser et al. 1985; Kaiser et al. 1992). This suggestion was meant to address an apparent contradiction between literature on naive physics (which suggested observers did not have veridical understanding of physical principles) and theories of displacement (some of which suggested observers did have veridical understanding of some aspects of physical principles). Furthermore, it was suggested that (a) if displacement was adaptive, then it should occur rapidly and without engaging attention or other cognitive resources (i.e., displacement should be automatic), and (b) one purpose of consciousness was to allow observers to learn and respond adaptively when mismatches between an automatically extrapolated position and subsequently sampled perceptual information occurred (i.e., when a target did not move as anticipated).

The idea that displacement involves implicit knowledge was bolstered by Freyd and Jones's (1994) observation that an observer's displacement pattern for targets ejected from a spiral tube did not correlate with that observer's performance on a paper and pencil test of explicit physical knowledge. Indeed, displacement patterns in Freyd and Jones were inconsistent with predictions based on veridical understanding of physical principles, as forward displacement was greater for targets that followed a physically incorrect spiral path after exiting a spiral tube than for targets that followed a physically correct straight path after exiting a spiral tube. Kozhevnikov and Hegarty (2001) reported that physics experts and physics novices exhibited greater forward displacement for smaller rising targets than for larger rising targets; however, physics experts correctly predicted larger objects would rise more rapidly than smaller objects, whereas physics novices incorrectly predicted smaller objects would rise more rapidly than larger objects. Kozhevnikov and Hegarty concluded that experts and novices had the same naive beliefs at the implicit level that influenced displacement, but that explicit physical knowledge could not penetrate the implicit level.

20.2.2.3 Naive impetus

Kozhevnikov and Hegarty (2001) suggested displacement attributed to representational momentum is more consistent with naive impetus theory than with Newtonian theory, and this is in accord with their findings regarding effects of target size on displacement of rising targets.[2] Additional evidence for the role of naive impetus in displacement was found in studies in which forward displacement of targets in launching effect displays (based on Michotte 1963) decreased relative to forward displacement of unlaunched control targets. According to naive impetus theory (McCloskey 1983), when a moving stimulus contacts a stationary target that results in the target moving, motion of the target is attributed to impetus imparted from the moving stimulus; an impetus that is believed to dissipate with subsequent target motion. If such a belief exists, then observers should expect the target to stop once the impetus dissipates below the threshold needed to maintain motion. Finke

[2] A theory of displacement based on naive impetus might seem just a special case of a more general theory of displacement based on implicit knowledge. For some observers, belief in naive impetus might specify the content of implicit knowledge; however, for other observers, belief in naive impetus might specify an explicit (but incorrect) physical principle those observers can clearly articulate (cf. McCloskey 1983).

et al. (1986) demonstrated forward displacement of a target decreased if observers expected the target to stop.

The idea that displacement reflects belief in naive impetus is consistent with the emphasis on the subjective consequences of physical principles on displacement in Hubbard (1999, 2006a). For example, when observers view an initially stationary physical object that begins moving immediately after being pushed, that pushed object subsequently slows and stops unless a compensating force (e.g., additional pushing) is applied. This reflects friction from the surface the object moves across or 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 being pushed will slow and stop unless a compensating force is applied. The resulting idea of impetus could allow sufficiently accurate prediction of the behavior of most physical objects in most situations, and so observers could more easily model the behavior of targets by using a simpler (but incorrect) "impetus" notion than by using a more complex (and correct) "momentum plus friction" notion (Hubbard 2004).

20.2.3 Neointernalization theories

Neointernalization theories combine elements of internalization theories and belief-based theories, thus allowing both implied physical principles and the observer's expectations to influence displacement. A theory based on second-order isomorphism is a general theory in which displacement results in part from properties of the functional architecture of mental representation, and a theory based on anticipatory consciousness is a general theory in which displacement results from a remapping of perceptual space to reflect the observer's intended motor activity.

20.2.3.1 Second-order isomorphism

Hubbard (1999, 2006a) suggested displacement resulted in part from second-order isomorphism between invariant physical principles that operate on physical objects and mental representations of those objects. This notion can be illustrated by considering how representational momentum is consistent with Shepard's (1975, 1981; Shepard & Chipman 1970) notion of second-order isomorphism of objects and mental images of those objects. In physical rotation, a physical object at orientation A must pass through intermediate orientation B before reaching orientation C, and this reflects a constraint on physical transformations. In mental rotation, a mental representation of an object depicted at orientation A must pass through intermediate orientation B before reaching orientation C, and this reflects a constraint on mental transformations. The mental representation of the physical transformation is a functional analogue of the physical transformation, that is, mental rotation is second-order isomorphic to physical rotation. A physical object rotating from orientation A to orientation C would also exhibit momentum, and this reflects a constraint on physical transformation. A mental representation of a physical object depicted as rotating from orientation A to orientation C would also thus exhibit a functional analogue of momentum (i.e., representational momentum).[3]

A second-order isomorphism between subjective aspects of invariant physical principles that operate on physical objects and mental representations of those objects provides a default displacement consistent with a modified view of spatiotemporal coherence that emphasizes subjective aspects of invariant physical principles. In the absence of additional physical or cognitive context, this default displacement takes the form of a vector of activation that determines the direction and magnitude of displacement of the target (see Hubbard 1995b). The presence of additional physical or cognitive context provides additional vectors of activation that are added to the default displacement, and so the observed direction and magnitude of displacement for a given target reflects a combination of (a) the default displacement due to invariant physical principles, and (b) influences due to information provided by physical or cognitive context. By allowing physical or cognitive context to modulate the default displacement, such an approach resonates with the importance of context emphasized by Gestalt psychologists. Much as any given element of a display must be understood in terms of its relationship to other elements of that display, so too the displacement of any given target can only be understood in terms of that target's relationship to the context or event structure within which that target is embedded.

20.2.3.2 Anticipatory consciousness

Jordan's (1998) discussion of a possible anticipatory role of consciousness in perception suggests displacement reflects the intentions and anticipations of an observer. That is, displacement results from remapping the perceptual space of an observer to reflect that observer's intentions and anticipations. This remapping is a natural consequence of a common coding structure in which action planning and perception share neural resources, and the represented location of the target reflects the ongoing interaction between the observer's action plans and the actual stimulus location rather than reflecting just the actual stimulus location. Furthermore, Jordan (1998) suggests that dynamics of the environment have resulted in sensory-motor coordination that reflects those dynamics; more specifically, that dynamics of the environment have been transferred, via natural selection, into the algorithms of sensory-motor control. As a result, the location of the target and the location of the observer are contextualized by the target's "anticipated" location. Such internalization is consistent with the shaping of the functional architecture of mental representation suggested by second-order isomorphism (Hubbard 2006a) and with feedforward modeling in which perceptual encoding reflects consequences of potential actions (e.g., Desmurget & Grafton 2003).

[3] There are other intriguing connections between imagery and representational momentum. Kelly and Freyd (1987) speculated representational momentum reflects analogue representation similar to that suggested to underlie imagery. Munger, Solberg, and Horrocks (1999) reported observers who exhibited greater representational momentum, exhibited faster mental rotation, and suggested observers "filled in" between inducing stimuli with processes used in mental imagery. Senior, Barnes, and David (2001) reported participants with higher scores on the Vividness of Visual Imagery Questionnaire exhibit greater representational momentum. Hubbard (2006a) speculated mental imagery exhibits the same directionality and continuity that characterize the spatiotemporal coherence that Freyd (1987) hypothesized to give rise to representational momentum.

20.2.4 Low-level theories

Low-level theories suggest displacement results from properties of low-level vision such as oculomotor behavior, motion aftereffects, and perceptual adaptation. These narrow explanations do not appeal to knowledge or experience beyond that arising from perception of the current target, and suggest displacement does not involve or result from memory or other high-level cognitive processes. A theory based on oculomotor behavior originally appeared intended as a general theory (e.g., Kerzel 2000; Kerzel et al. 2001), but it only applies to targets exhibiting continuous motion (e.g., Kerzel 2003a,b). A theory based on motion aftereffects and perceptual adaptation is a specific theory applied to displacement measured by probe judgment.

20.2.4.1 Oculomotor behavior

Kerzel (2000; Kerzel et al. 2001) noted that pursuit eye movements overshoot the final position of a continuously moving target, and coupled with findings that memory for the position of a target is biased toward the fovea (e.g., Müsseler et al. 1999), it was suggested that forward displacement reflects movement and position of the eyes. Also, Kerzel (2000) noted visual persistence of a target (subjectively visible for 50–60 milliseconds after the target objectively vanished), coupled with the tendency for pursuit eye movements to overshoot the final position of a continuously moving target, suggests forward displacement reflects properties of the eyes and eye movements. Kerzel (2002c) presented probes during the brief interval in which visual persistence occurred, and the point of subjective equality in judgments of the alignment of the probe and the target was shifted forward in the direction of motion. It was also suggested that predictive eye movements accounted for changes in displacement accompanying expected changes in target direction (Kerzel 2002c). Furthermore, displacement previously attributed to representational friction (Hubbard 1995a; see Kerzel 2002c) or to representational centripetal force (Hubbard 1996; see Kerzel 2003b) is decreased or eliminated for continuous motion targets when observers cannot track the target.

Given the consequences of pursuit eye movements, foveal bias, and visual persistence, Kerzel (2000, 2002c; Kerzel et al. 2001) suggested forward displacement resulted from oculomotor behavior and was at least partly perceptual. In support of this, Kerzel (2002b) reported memory averaging of a target and nontarget stimulus occurred only if the nontarget stimulus was present when the target vanished or shortly thereafter. Indeed, Kerzel (2002c, p. 692) claimed "perceptual factors account for a large proportion of a mislocalization that was previously thought to result from processes operating in memory." Even so, an apparent challenge to an oculomotor behavior theory is that pursuit eye movements are not evoked by implied motion or frozen-action stimuli. In the absence of pursuit eye movements, oculomotor behavior cannot account for displacement with implied motion or frozen-action stimuli. However, Kerzel et al. (2001) argued fixation might still be shifted in the direction of motion even in the case of implied motion stimuli. Later, though, Kerzel (2003b; see also Kerzel 2005) suggested oculomotor behavior cannot be the only source of displacement, and that displacement with implied motion stimuli reflects high-level factors.

20.2.4.2 Motion aftereffects/perceptual adaptation

Bertamini (2002) suggested the greater likelihood of a *same* response to probes beyond the final position of a moving target reflected motion aftereffects and perceptual adaptation. If observers view motion in a specific direction, then a motion aftereffect will raise their threshold for detecting subsequent motion in that direction (Bonnet et al. 1984). Such observers might be less likely to perceive probes slightly beyond the actual final position than probes slightly behind the actual final position as different from the actual final position of the target. Similarly, if observers attend to a specific direction of motion, then they exhibit less sensitivity to subsequent events in that direction (Raymond et al. 1998). Thus, forward displacement results from asymmetrical change in sensitivity rather than from anticipation regarding the target. Bertamini's account stresses passive loss of sensitivity rather than active production of displacement, but it is not clear whether a passive loss of sensitivity is completely consistent with observations by Freyd and Finke (1984) and Hubbard and Bharucha (1988) that motion aftereffects are in the direction opposite to representational momentum and so could not actively produce representational momentum.

20.2.5 Network models

Although internalization, belief-based, and neointernalization theories specify possible cognitive mechanisms involved in displacement, those theories do not explicitly address implementation. Network models offer ways in which cognitive mechanisms of displacement might be implemented, and are typically general models that suggest displacement results from properties of network representations of the target and of the context within which the target is embedded (i.e., displacement results from patterns of connectivity and spreading activation within a network architecture). Given that other approaches discussed in Section 20.2 involve different levels of explanation than do network models, network models should be viewed as complementing rather than competing with other approaches.

20.2.5.1 Vector addition (weighted averaging)

One way to characterize how influences of implied physical principles and influences of physical or cognitive context contribute to displacement is to consider individual influences as separate vectors (Hubbard 1995b). The direction and magnitude of each vector reflects properties of the functional architecture of representation or information regarding the observer's knowledge or beliefs, and the displacement of a given target reflects a combination (e.g., summation or weighted average) of these vectors. Such vectors can be broadly construed as corresponding to magnitudes and directions of activation within a network architecture that preserve functional mapping between physical space and represented space. As a target moves through space, it traces a pattern of activation through the network. Nontarget context such as nearby surfaces and objects activates network locations corresponding to those surfaces and objects. Once a network location is activated, that activation spreads along excitatory or inhibitory pathways to neighboring locations. The remembered location of a target corresponds to the center of activation attributed to that target, and the difference between the center of activation and the network location corresponding to the veridical location of the target determines the direction and magnitude of displacement.

Hubbard (1995b) suggested how different influences on displacement might be modeled in a network architecture. Implied physical principles might be modeled by having activation channeled in specific directions (e.g., representational momentum as stronger excitatory activation along the anticipated path of motion, representational gravity as stronger flow of activation downward, and representational friction as inhibitory activation from a contacted region). Memory averaging might be modeled by residual activation from previous locations of the target, or by spreading activation from nearby nontarget stimuli, combining with activation from the final location of the target. This additional activation would shift the averaged center of activation representing the target toward those previous locations or nontarget stimuli. An observer's expectations could provide excitatory activation (priming) to network locations that corresponded to an anticipated position or provide inhibitory activation to network locations that did not correspond to an anticipated position. As noted earlier, the displacement of a given target would reflect some combination of all of these (and possibly other) influences.

20.2.5.2 Erlhagen-Jancke model

Erlhagen and Jancke (1999, 2004) developed a mathematical model generally consistent with speculations in Hubbard (1995b). One mechanism in the model involves interacting excitatory or inhibitory cell populations. Localized activity corresponds to the represented stimulus, and this activity moves through the network. Recurrent interactions within the network develop a wave pattern that sustains dynamic transformation (i.e., prolongs changes in patterns of activation) for a brief time after stimulus offset. After stimulus offset, excitatory activity continues to increase, reaches a maximum, and then decays back to a resting level. A second mechanism in the model involves cognitive factors (e.g., prior knowledge, action plans) that are modeled as additional dynamic inputs and influence the extent to which the cell population response overshoots final target position. If the threshold for gating recurrent interactions is low, there is larger extrapolation of past information into the future, and forward displacement of represented position occurs. If the threshold for gating recurrent interactions is high, as would happen if observers expect a target to reverse direction, then backward displacement in represented position occurs.

The Erlhagen-Jancke model addresses several findings in the displacement literature. First, the model addresses forward displacement with continuous motion and with implied motion. With continuous motion, continuous sampling produces a traveling wave of activity that produces displacement. However, with implied motion, the interstimulus intervals typically used (250 milliseconds) are too long to permit generation of such a traveling wave, and strictly bottom-up activity would not produce displacement. Erlhagen (2003) suggests that in such circumstances a bottom-up signal is continuously compared with an internal model that predicts future states of the moving stimulus, and this top-down influence bridges the interstimulus intervals between inducing stimuli, thus allowing a traveling wave capable of producing displacement to be generated. Second, the model addresses changes in displacement when observers expect a target to bounce off a barrier by incorporating hyperpolarizing units coding for position in the area of the barrier (thus raising the threshold), and so recurrent interactions are not sufficiently strong to allow forward displacement. Third, the model addresses effects of oculomotor action plans by adding a predictive signal that specifies the direction of an observer's gaze.

20.2.5.3 Bow-wave model

Müsseler et al. (2002) proposed the bow-wave model to account for representational momentum, the Fröhlich effect (forward displacement of the remembered initial location of a moving target; Müsseler & Aschersleben 1998), and the flash-lag effect (a briefly presented [flashed] stationary object aligned with a moving stimulus is perceived to lag behind the moving stimulus; Nijhawan 2002). The bow-wave model assumes a moving target produces activation within a network representing spatial location. Adjacent positions in the direction of movement are differentially primed by spreading activation from the target (cf. Hubbard 1995b). As the target approaches specific positions along its path, additional activation at those positions is accumulated, and a stimulus-driven "bow-wave" of activation occurs and spreads forward (cf. Erlhagen & Jancke 1999, 2004). A Fröhlich effect occurs because initial movement of the target skews activation forward; representational momentum occurs because activation requires time to decay, and during the course of decay, remaining activation continues to spread forward; and the flash-lag effect occurs because neural processing of a moving stimulus is faster than neural processing of a stationary (and flashed) target, and so the center of activation for the moving stimulus is displaced ahead of the center of activation for the flashed target.

20.2.6 Evaluating the theories and models

The theories and models discussed in Section 20.2 address different, and often nonoverlapping, types of data. Many specific theories and models arose from critiques of earlier studies or from criticisms of general theories and models, and might not have been intended as general accounts of displacement. Even so, if such specific theories or models are valid, they would presumably be consistent with other findings. Thus, it is useful to evaluate how specific theories and models, as well as how general theories and models, account for displacement over a wide range of experimental data. Such a summary is provided in Table 20.1, and whether each of the theories and models discussed in Section 20.2 is consistent with, inconsistent with, or doesn't address each of the experimental findings mentioned in Section 20.1 is noted. Effects of some variables (e.g., velocity) are consistent with many of the theories and models. However, effects of other variables (e.g., expectations regarding future motion, fixation away from a smooth motion target) are consistent with some theories and models and inconsistent with others. Effects of still other variables are not addressed by each of the theories and models, and it is not clear whether those effects are consistent or inconsistent. Neointernalization theories and network models seem consistent with more data than are other approaches, but there is still a significant amount of data that each theory or model does not address.

20.3 Toward a future theory of displacement

As shown in Section 20.2, there are a variety of theories and models regarding displacement and representational momentum, but no current theory or model adequately addresses all of the data on displacement and representational momentum, nor do investigators agree on what is the best approach. Some theories address very specific low-level mechanisms (e.g., pursuit eye movements and visual persistence), whereas other theories address more general high-level mechanisms (e.g., beliefs regarding a target or the operation of physical systems). What would be more useful is a more unified theory that addresses a broader range of data, and there are at least two different ways to approach the development of such a theory. One way is to integrate existing approaches into a larger, more inclusive theory, and this would be a more bottom-up approach (e.g., Kerzel 2005, 2006). A second way is based upon development of a computational theory of displacement, and this would be a more top-down approach (e.g., Hubbard 2005, 2006b).

20.3.1 Attempts at unification

Although some of the theories reviewed in Section 20.2 could be considered general theories intended to apply to a broad range of displacement data, none of those could be considered fully unified theories. By combining internalization and belief-based approaches, neointernalization theories provide an initial step toward a broader and more unified theory, but many aspects of the data nonetheless remain unaddressed (e.g., many characteristics of the observer). Further development of network models might produce a broader and more unified theory, and although such development could be useful for prediction and modeling, it is not clear that such models would be truly explanatory. There have recently been two suggestions regarding a more unified theory: Kerzel's three-factor approach and Hubbard's computational theory approach.

20.3.1.1 Kerzel's three-factor approach

A bottom-up approach to developing a more general theory of displacement might consider taking some of the separate theories discussed in Section 20.2, and then combining those to produce a larger and more comprehensive theory. Such an approach was taken by Kerzel (2005, 2006) in proposing a three-factor approach that brought together results from his work on effects of eye movements, response type, and motion type. This approach suggests the occurrence of forward displacement is determined by a combination of (a) the presence or absence of eye movements, (b) whether the response is verbal or motoric, and (c) whether target motion appears smooth and continuous or appears discrete and implied. Kerzel suggests pursuit eye movements contribute to forward displacement for targets exhibiting smooth motion, but not for targets exhibiting implied motion. Similarly, forward displacement can be produced by the motor system when a person reaches to indicate target position, but not when a person renders a verbal judgment regarding whether a subsequently presented probe is at the same position where the previously viewed target vanished. In the three-factor approach, the mechanisms that produce forward displacement exist primarily at the perceptual or motoric level rather than at the cognitive level, and there is no internalization or incorporation of physical principles.

Although the three-factor approach addresses displacement in a wider range of stimulus and response types than do any of the three factors taken individually, it does not address some key displacement data (e.g., downward displacement along the orthogonal axis of horizontally moving targets, forward displacement in frozen action photographs). More critically, some factors are treated as causal (rather than mediating or moderating) while other (often higher-level) factors might be more properly regarded as causal. For example, pursuit eye movements are treated as causal of forward displacement when observers view continuous motion (see Kerzel 2000), but it seems more parsimonious that causality should be assigned to high-level expectations regarding continuation of motion (and that drive such predictive or anticipatory eye movements) given that high-level expectations are already evoked to explain displacement when observers view implied motion. Similarly, differences in displacement related to expectations regarding changes in target behavior (e.g., direction of motion) are more parsimoniously attributed to high-level expectations than to multiple different low-level mechanisms (cf. Kerzel 2002; but see Hubbard 2006b). Also, by positing separate and unrelated mechanisms for the same displacement pattern in different types of stimuli, displacements resulting from different types of stimuli are viewed as separate phenomena, making it more difficult to determine appropriate generalizations or constraints.

20.3.1.2 Hubbard's computational theory approach

A top-down approach to developing a more general theory of displacement might focus on the function of displacement and on the information processing benefits of displacement. Hubbard (2005, 2006a) proposed that a theory of representational momentum should focus on a computational theory of displacement rather than on implementation per se. The computational theory of a process (or function more generally) addresses how that process helps an organism and what problem that process solves (Marr 1982). A computational theory of representational momentum would begin by considering how displacement might help an organism. Given that forward displacement resulting from implied motion or from continuous motion anticipates the behavior of a target, such displacement could be useful in spatial localization of stimuli in the environment, navigation, and survival. For example, a predator among shadows and occlusions in a jungle is visible only intermittently (similar to implied motion), but a predator in open grassland is visible continuously (similar to continuous motion). In both jungle or grassland settings, accurate anticipation of a predator's location would be adaptive, and forward displacement in the represented location of a predator in either setting would serve the purpose of aiding survival.

A computational theory addresses constraints on the information being computed, but does not address specific mechanisms regarding how the computation is implemented (e.g., see Dawson 1998). Indeed, given that different types of information are available in different settings, it would not be surprising if displacement in different settings were implemented in different ways. An approach based on computational theory views forward displacement resulting from implied motion or continuous motion as examples of the same phenomenon, and so seeks a deeper and broader level of explanation that would then guide a subsequent search for and interpretation of the specific representations, algorithms, and implementations of displacement. By focusing initially on the "big picture" rather than on the specific details of representation, algorithm, and implementation, such an approach is more likely to allow discovery of relevant generalizations and constraints.

20.3.2 Considerations for a future theory

There are several considerations for any future (and more general or unified) theory of displacement and representational momentum. Any future theory should address the full breadth of data and the multiple levels of processing and representation involved in displacement and representational momentum. Given that both low-level variables and high-level variables influence displacement, any future theory should address how information from one level can influence or be integrated with information from another level. Finally, any future theory should explicitly address the function of displacement, as such a consideration could help elaborate a subsequent computational theory of displacement.

20.3.2.1 Breadth of data

As noted in Section 20.2, many of the earlier theories of representational momentum were specific theories that addressed displacement resulting from a specific type of stimulus or response. Such specific theories tended to ignore the existence of displacement resulting from other types of stimuli or responses, and as a result, researchers sometimes appeared to not realize the limitations of those specific theories. Along these lines, consideration of displacement should not be limited to just forward displacement along the axis of motion, but should include other potentially related displacements (e.g., downward displacement attributable to implied gravity, displacement toward a nearby landmark).[4] Similarly, consideration of forward displacement should not be limited to effects of momentum per se, but

[4] It is unclear whether the types of displacement related to representational momentum might be related to other types of displacement such as Fröhlich effect, onset repulsion effect, or flash-lag effect. There have been preliminary attempts to account for these different types of displacement as well as representational momentum within a common mechanism (e.g., Müsseler et al. 2002) and to specify the relationship of representational momentum to these other displacements (e.g., Munger & Owens 2004; Hubbard 2006a), but more work remains to be done.

should address other variables that might also influence forward displacement. Examination of Table 20.1 suggests previous theories often addressed just one or two of the four types of characteristics (target, display, context, observer), but any future theory should address all four types of characteristics. In general, high-level theories (or theories involving high-level mechanisms) appear to have greater breadth than do low-level theories. Similarly, network models appear to have greater breadth, but this might just reflect their greater level of abstraction.

20.3.2.2 Multiple levels

Marr (1982) argued that a complete understanding of a given process would require understanding at each of the levels of computational theory, representation and algorithm, and implementation. Many of the theories in Section 20.2 focused on the levels of implementation or of representation and algorithm, and it is not clear whether a larger theory cobbled together from separate and specific theories of implementation or of representation and algorithm would sufficiently address issues at the computational theory level. Even if a Marr framework for displacement is rejected, any future theory of displacement must still address the issue of multiple levels of representation, as empirical findings regarding effects of both low-level variables and high-level variables on displacement suggest the existence of multiple levels of representation. The presence of low- and high-level variables is consistent with the existence of other hierarchical structures in perceptual (e.g., Treisman & Gelade 1980), cognitive (e.g., Rosch et al. 1976), and motor (e.g., Rosenbaum et al. 1983) activity. Postulation of a hierarchical structure in displacement is consistent with proposals that (a) top-down expectation can influence the perceived location of a target, and (b) bottom-up activity can modulate the remembered location of a target. Indeed, it is possible that aspects of displacement attributed to perception (e.g., Kerzel 2002c) involve such a top-down influence on perception that is based on information or expectations in memory.

20.3.2.3 Integration of levels

Given that both low- and high-level variables influence displacement, any unified account must address how to bridge low-level variables and theories to high-level variables and theories. However, acknowledgment that both low- and high-level variables can influence displacement does not entail that variables at different levels are equivalent or equal in importance (e.g., high-level expectations might drive low-level eye movements). For example, given the greater breadth of high-level theories noted earlier, any integration of low- and high-level information might be more easily accomplished at a high level. A high-level mechanism might more easily access information from high-level (e.g., expectations and beliefs regarding target motion) or low-level (e.g., pursuit eye movements) sources, and might more easily control high-level (e.g., allocation of attention) or low-level (e.g., anticipatory eye movements) processes. Also, as Hubbard (2005) noted, a high-level mechanism that biases encoding or retrieval of location would be consistent with high-level schemata, scripts, and frames that bias encoding or retrieval in other domains of memory. Any future theory of displacement should seek not merely an integrated or unified theory of displacement and representational momentum, but to integrate displacement within the larger range of cognitive processes organisms engage in on a daily basis.

20.3.2.4 Focus on function (and functionalism)

As noted earlier, a computational theory of a given process is not initially concerned with implementation of that process. Along these lines, a functionalist approach suggests that the usefulness or appropriateness of a cognitive theory of a given process does not require a given outcome (e.g., forward displacement) be instantiated by the same mechanism or implementation each time that outcome occurs; rather, what is important is the relationship between that outcome and other cognitive processes, sensory inputs, or motor outputs. Displacement for implied motion targets and continuous motion targets reflects the same relationship between inputs and outputs (i.e., memory for a moving target is displaced forward), and so displacement for both types of stimuli could reflect the same general function, even though displacement for implied motion targets and continuous motion targets might involve different forms of implementation. A unified theory of displacement could potentially be based on the idea that different examples of displacement involve the same function, rather than on findings that different examples of displacement are implemented in different ways. Also, a focus on function would shed additional light on how displacement aids the organism, what problems displacement helps solve, and would help elaborate a computational theory of displacement.

20.4 Conclusion

Memory for the final location of a moving target is often displaced in the direction of previous or anticipated target motion, and this has been called *representational momentum*. A wide range of theories and models have been proposed to account for representational momentum and related types of displacement, with some theories applying only to a specific type of stimulus or response, and other theories applying to a wider range of stimulus or response types. These theories and models cover a range of approaches, from low-level explanations based on oculomotor behavior, motion aftereffects, and perceptual adaptation, to high-level explanations based on an observer's beliefs regarding physical systems and properties of mental representation. A classification system was proposed that involves (a) internalization theories, (b) belief-based theories, (c) neointernalization theories, (d) low-level theories, and (e) network models. Consistencies and inconsistencies of each of the individual theories and models with empirical findings were noted. Neointernalization theories and network models seem consistent with more overall data than are other types of theories, but no single theory or model accounts for all the existent data on displacement or representational momentum.

The possibility of a more unified theory of displacement was addressed. Recent approaches involving multiple factors (eye movements, mode of responding, type of motion) and a proposal for a computational theory of displacement were briefly discussed, and it was suggested that any future theory of displacement (in general) and representational momentum (in particular) should be based on a consideration of function and not the different implementations that might contribute to production of displacement or representational momentum. Several considerations for future development were described including addressing (a) an increased breadth of data, (b) the existence of multiple levels of processing, (c) how low- and high-level variables and information might be combined or integrated, and (d) the function of displacement. Finally, a parallel between representational momentum and high-level schemata, scripts, and frames that bias encoding and retrieval in other domains of cognition was noted, and it was suggested that any future theory of displacement should try to integrate representational momentum and displacement within this larger range of cognitive processes.

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