Momentum-like effects and the dynamics of perception, cognition, and action

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Abstract

In a momentum-like effect, the likely future state of a current action or process is extrapolated. Momentum-like effects have been suggested to reflect dynamic processes, but such effects have not often been discussed in the broader literature on dynamic approaches to perception, cognition, and action. Several momentum-like effects are briefly described, and attempts to formulate dynamic theories of such effects are considered. Issues regarding dynamic representation that are relevant for theories of momentum-like effects (whether contingencies are invariant, stochastic, or arbitrary; bridging gaps between perception and action and between action and reinforcement; adaptiveness of such effects; influences of an observer's knowledge, beliefs, and expectations; relationship of momentum-like effects to naïve physics and perception of causality) are discussed. Issues highlighted by a consideration of momentum-like effects relevant for dynamic approaches to other phenomena (multiple meanings and senses of “dynamic,” different meanings and connotations of “continuation” and “extrapolation,” perceptual inference of subjective or objective consequences, importance of time scale and temporal information, importance of the computational theory level, momentum-like effects as an example of predictive processing) are also discussed. Momentum-like effects provide examples of relatively simple dynamic processes that reveal and highlight issues relevant for study of dynamic approaches in a wide range of perceptual, cognitive, and action phenomena.

Keywords Perception and action · Momentum-Like effect · Cognitive dynamics · Predictive processing · Anticipatory representation

Introduction

Although dynamic theories and models have been proposed for many perceptual, cognitive, and action processes (e.g., see Juarrero, 2002; Kelso, 1995; Port & van Gelder, 1995; Schöner, Spencer, and the DFT Research Group, 2016; Thelen & Smith, 1994), it is perhaps with momentum-like effects that some of the clearest examples and implications of dynamic approaches to understanding perception, cognition, and action can be observed. However, the wider literature on dynamic approaches to perception, cognition, and action has often not considered momentum-like effects. Relatedly, literatures on different

momentum-like effects have been relatively isolated from each other, and the more general notion of a single mechanism capable of generating consistent momentum-like effects across multiple domains and multiple time scales was not suggested until recently (e.g., Hubbard, 2014, 2015a, 2015b, 2017b). Several types of momentum-like effect are briefly described, and then an early theory of dynamic representation that was proposed for one type of momentum-like effect, and subsequent changes and extensions to that theory in light of subsequent knowledge of other types of momentum-like effect, are discussed. The possibilities of basing a general theory of momentum-like effects on a specific momentum-like effect or on a consideration of the momentum metaphor and more general top-down computational theory are considered. Empirical findings and theoretical notions that would constrain any potential dynamic theory of momentum-like effects are also considered. Finally, implications of momentum-like effects for dynamic theories

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and models of a wider range of perceptual, cognitive, and action phenomena are considered.

Momentum-like effects

There are at least five different momentum-like effects, and these include representational momentum, operational momentum, attentional momentum, behavioral momentum, and psychological momentum. The first three have been characterized as involving effects primarily across space (Hubbard, 2014), and the latter two have been characterized as involving effects primarily across time (Hubbard, 2015a); in all five types, though, there are predictive changes across both space and time. Additionally, there has been a proposal for musical momentum, although data regarding the possibility of musical momentum are less clear.

Representational momentum

An individual who indicates the remembered final position of a previously viewed moving target is likely to indicate a position farther forward in the direction of motion than is the actual position, and this has been referred to as *representational momentum* (Freyd & Finke, 1984). Representational momentum is exhibited for targets that exhibit smooth continuous motion (Hubbard & Bharucha, 1988), implied motion (Freyd & Finke, 1984), and for a single frozen-action stimulus (e.g., photograph of a person walking in a specific direction; Futterweit & Beilin, 1994), and representational momentum has been assessed by having experimental participants use a computer mouse to position a cursor at the remembered final target location (Hubbard & Bharucha, 1988), judge whether a subsequently presented probe is at the same location as the remembered final target location (Freyd & Finke, 1984), or reach out and touch on a display (e.g., touchscreen) the remembered final target location (Ashida, 2004). Representational momentum is influenced by many variables including velocity of the target, direction of target motion, allocation of attention, retention interval, presence and proximity of nontarget stimuli to the target, attributions of causality regarding target motion, expertise of the observer in the target domain, the observer's action plans, expectations regarding changes in direction or velocity of target motion, contrast between the target and the background, and the semantic category of the target (for reviews, Hubbard, 1995b, 2005, 2014, 2018), and there are several theories of representational momentum (for review, Hubbard, 2010).

Operational momentum

An individual who estimates the sum or difference of an addition or subtraction, respectively, is likely to overestimate the

amount of change (e.g., estimate a larger number for addition and a smaller number for subtraction), and this has been referred to as *operational momentum* (McCrink, Dehaene, & Dehaene-Lambertz, 2007). Operational momentum occurs with symbolic stimuli such as numerals and equations (Lindemann & Tira, 2011) and non-symbolic stimuli such as clusters of different quantities of dots (McCrink et al., 2007) and pointing to a location along a number line (Pinhas & Fischer, 2008). Variables that influence operational momentum include distance along the number line, direction along the number line, magnitude of the operands, age of the individual, and allocation of attention (for review, see Hubbard, 2014). Theories of operational momentum include motion in numeric space (i.e., along the number line, McCrink et al., 2007), attentional shifts (Knops, Viarouge, & Dehaene, 2009), and a general heuristic or bias to accept a larger quantity if adding and a smaller quantity if subtracting (McCrink & Wynn, 2009). It is possible that operational momentum might be a special case of representational momentum that occurs along the mental number line (Hubbard, 2014), and in such a view, operational momentum is a consequence of the spatialization of numerical or quantitative information. Whether operational momentum exists for mathematical operations other than addition or subtraction is not yet clear.

Attentional momentum

If attention is being shifted across space, individuals are faster to detect a target that lies further ahead in the direction of the current movement of attention than to detect a target that lies an equal distance away in some other direction, and this has been referred to as *attentional momentum* (Pratt, Spalek, & Bradshaw, 1999). Variables that influence attentional momentum include direction of attention shift, distance of attention shift, eccentricity of the target to be detected, allocation of attention, and eye movements of the individual (for review, see Hubbard, 2014). Attentional momentum has been attributed to a momentum inherent in the shifting of attention across space; because of this momentum, more time is required to stop the shift of attention in the current direction and begin movement in a different direction than to continue movement in the current direction.¹ Attentional momentum might be related to representational momentum, as judgment of a probe is facilitated if the probe is slightly in front of the final target location relative to if the probe is slightly behind the final

¹ Although not addressed in the literature, there is no a priori reason why attentional momentum must be limited to shifts of attention in three-dimensional physical (or visual) space. It seems possible that effects of attentional momentum could occur in any type of representational format that preserved metric properties of physical space (e.g., representational momentum is also found in auditory frequency space, e.g., Johnston & Jones, 2006; operational momentum has been hypothesized to reflect shifts in numerical space, e.g., Knops, Viarouge, & Dehaene, 2009).

target location (Kerzel, Jordan, & Müsseler, 2001) and representational momentum occurs for stationary objects in a scene if the viewpoint into that scene is shifted (Munger, Dellinger, Lloyd, Johnson-Reid, Tonelli, Wolf, & Scott, 2006). Relatedly, the allocation of attention can also influence representational momentum, as representational momentum is typically decreased if another stimulus or task is presented concurrently with the target (Hayes & Freyd, 2002). However, attentional momentum has been claimed to be distinct from representational momentum (e.g., Pratt et al., 1999).

Behavioral momentum

Just as a physical body continues in motion until acted upon by an outside force, ongoing behavior maintained by constant reinforcement continues at a steady rate until acted upon by an external variable, and this has been referred to as *behavioral momentum* (Nevin, 2015; Nevin, Mandell, & Atak, 1983). In other words, if an individual receives a consistent rate of reinforcement for a given behavior, then that behavior is more likely to continue. Unlike other momentum-like effects, behavioral momentum is often studied in developmentally disabled human populations in which it is also used as a treatment (e.g., Dube, Ahearn, Lionello-Denolf, & McIlvane, 2009; Mace, Lalli, Shea, Lalli, West, Roberts, & Nevin, 1990; Parry-Cruwys, Neal, Ahearn, Wheeler, Premchander, Loeb, & Dube, 2011) or in nonhuman animals (e.g., Nevin, Tota, Torquato, & Shull, 1990; Podlesnik & Shahan, 2009, 2010). Variables that influence behavioral momentum include schedule of reinforcement, reinforcement rate, whether a preceding task exhibited a typically low level or high level of compliance, reinforcer quality, presence of noncontingent reinforcement, presence of alternative reinforcement, extinction, resurgence, attention, and psychopathology (for review, Hubbard, 2015a). Also, unlike other forms of momentum-like effects, behavioral momentum is firmly grounded in a mathematical framework (Nevin, 1988, 1992, 2012; Nevin & Shahan, 2011) and in learning theory (Nevin, 1992; Nevin & Grace, 2000).

Psychological momentum

If an individual experienced success or failure at a given task in the recent past, then that success or failure is often believed to influence the likelihood of success or failure on a similar task in the present or near future, and this has been referred to as *psychological momentum* (Iso-Ahola & Dotson, 2014; Iso-Ahola & Mobility, 1980). Psychological momentum can be positive (i.e., previous success leading to future success) or negative (i.e., previous failure leading to future failure), but both positive and negative forms of psychological momentum reflect a continuation of the direction of previous action. In early studies of psychological momentum, an individual viewed (e.g., Gernigon, Briki, & Eykens, 2010) or competed

(e.g., Shaw, Dzewaltowski, & McElroy, 1992) with another individual, but more recent investigations have broadened the application of psychological momentum beyond competition to include completion of everyday activities (e.g., Markman & Guenther, 2007). Variables that influence psychological momentum include valence, task duration, prior probability, preceding performance, gender, whether feedback is provided, ability, self-efficacy, and the extent of the individual's control (for review, Hubbard, 2015a; also Iso-Ahola & Dotson, 2014, 2016). Theories of psychological momentum involve the degree of control in progressing toward a goal (Vallerand, Colavecchio, & Pelletier, 1988), labeling of previous performance (Comelius, Silva, Conroy, & Petersen, 1997), an individual's perceptions of progress toward a goal (Taylor & Demick, 1994), naïve beliefs about momentum and physics (Markman & Guenther, 2007), and the intensity, frequency, and duration of previous success (Iso-Ahola & Dotson, 2014, 2016).

Musical momentum

Johnson and Larson (2003) suggested several ways in which musical motion is analogous to motion of physical objects, and Larson (2004, 2012) proposed the idea of musical forces and suggested that musical forces were analogous to forces that operate on physical objects. Of particular relevance to theories of momentum-like effects is Larson's notion of musical inertia, which was defined as the tendency of pitches or rhythms to continue in their current pattern. Larson (2012) reviewed evidence consistent with the notion of musical inertia, and Hubbard (2017a) discussed additional findings consistent with musical inertia. Larson suggested that musical inertia was similar to representational momentum in several ways; indeed, he suggested that musical inertia might reflect a special case of representational momentum involving perceived motion in a musical stimulus. Hubbard (2017a) presented a detailed comparison of representational momentum and musical inertia, discussed how a potential musical momentum offered a single unifying mechanism for several phenomena previously accounted for by different mechanisms (e.g., auditory streaming and perceptual grouping, auditory kappa and tau effects, sensorimotor synchronization), and listed several other consequences of a potential musical momentum. Even so, given differences in the time scales of musical inertia and representational momentum, it is unlikely that momentum-like effects in music are a special case of representational momentum; however, it is not yet clear if momentum-like effects in music reflect a special case of behavioral momentum or psychological momentum with musical stimuli or reflect a unique form of momentum-like effect.

Dynamics and momentum-like effects

The first application of notions regarding dynamic processing to momentum-like effects was by Freyd (1987), who based her theory on findings regarding representational momentum. Hubbard (2014, 2015a, 2015b, 2017b) attempted to extend Freyd's theory to include other types of momentum-like effects, and these efforts were based primarily on the observation that all momentum-like effects appear to involve continuation of a current action or process. Freyd's initial theory and Hubbard's subsequent extension are described, and issues regarding the definition of "dynamic," continuation and extrapolation, and basing a general theory of momentum-like effects on different specific momentum-like effects or on a momentum metaphor and computational level theory are considered.

Defining "dynamic"

A critical aspect of any dynamic approach to momentum-like effects is defining what is meant by "dynamic." This term has been used in different ways by different investigators, and two primary meanings will be discussed here. One meaning of "dynamic" is a colloquial meaning and simply refers to a change in the stimulus (e.g., target movement, Höffler & Schwartz, 2011) or response (e.g., motor movement, Tabatabaieian, 2018) over time. In some ways, this meaning of dynamic is trivial, as nearly all mental representations exhibit some change over time (e.g., Bartlett, 1932; Graesser & Nakamura, 1982; van Kesteren, Rijpkema, Ruiter, & Fernández, 2013; etc.); even so, this meaning of dynamic does acknowledge the importance of time and temporal information, and there are two senses in which temporal information is important. In the first sense, an otherwise static and stable representation is operated on by a process involving temporal information that is external to or separate from the original representation. In the second sense, temporal information is an intrinsic part of the representation. The critical difference between these two senses involves the extent to which the representation could be meaningful and/or useful if temporal information were removed (cf. Freyd, 1987). The former is consistent with a representation being meaningful and useful in the absence of temporal information, whereas the latter suggests meaningfulness and usefulness would be eliminated without inclusion of temporal information. Many examples of learning and cognition would seem more compatible with the latter (e.g., removing temporal information would render it more difficult to distinguish between cause and effect; similarly, the temporal relationship between a response and a reinforcer is critical in learning).

A second meaning of "dynamic" is a technical meaning drawn from physics and refers to the presence of force. There is a strong sense and a weak sense of this meaning. In the strong sense, mental representations possess force, and this

is clearly untenable (e.g., a neural encoding of a collision event would not involve neurons colliding with each other). In the weak sense, mental representations contain or encode information regarding force. Such information can potentially be in any format, but it is important that the representation of the qualities of force be isomorphic to the actual qualities of force experienced or exhibited by the referent physical object. One such potential isomorphism builds on Shepard's (1975, 1981) ideas of second-order isomorphism that were based on studies of mental imagery. For example, Shepard suggested that just as a physical object rotating from orientation A to orientation C must pass through an intermediate orientation B, so too must the mental representation of an object rotating from orientation A to orientation C pass through an intermediate orientation B. In an extension of Shepard's idea, Hubbard (2006a, 2017b) proposed that just as a distal object rotating from orientation A to orientation C must exhibit physical momentum, so too would the mental representation of an object rotating from orientation A to orientation C exhibit an analogue of momentum (i.e., representational momentum). As a faster rotation would require less time to traverse a given distance and would involve more force (and result in larger representational momentum, Munger, Solberg, & Horrocks, 1999), this proposal is consistent with both meanings of "dynamic" and with Shepard's original conception (i.e., "rotate an image") and Kubovy's (1983; Kubovy & Epstein, 2001) alternative conception (i.e., "image a rotation") of imagery.

Continuation and extrapolation

Different types of momentum-like effects involve continuation or extrapolation of the representation of a current action or process to a probable future state of that action or process. The literatures on momentum-like effects often appear to use "continuation" and "extrapolation" as synonyms, although the connotations of the two terms are slightly different, with "continuation" implying a more passive process and "extrapolation" implying a more active process. Freyd (1987) suggested continuation (which she referred to as "the basic phenomenon") was characteristic of dynamic representation, and extrapolation could be similarly suggested to be characteristic of dynamic representation. Given that continuation and extrapolation are characteristic of momentum-like effects by definition, momentum-like effects would thereby reflect or involve dynamic representations and processes. Importantly, continuation and extrapolation are always in the direction of the anticipated future change, even if the anticipated direction of change differs from the actual current direction (e.g., Hubbard & Bharucha, 1988). In order to be maximally useful, the continuation or extrapolation of an action or a process is largely automatic (indeed, decreasing attention allocated to a target increases the momentum-like effect, Hayes & Freyd, 2002; McCrink & Hubbard, 2017), although the direction

and magnitude of continuation or extrapolation can be influenced by stimulus-specific or task-specific explicit knowledge, beliefs, and expectations and by the learning history of the individual. Also, the consistent continuation or extrapolation in the direction of change demonstrates that momentum-like effects reflect a specific bias rather than just increased variance or uncertainty.

There are at least two types of continuation or extrapolation that might occur. The first type involves a specific type or direction of change (e.g., a moving target is changing in location, and continuation or extrapolation of a future location of that target continues until momentum is dissipated). Relatedly, acceleration (in which momentum increases) or deceleration (in which momentum decreases) leads to a larger or smaller momentum-like effect, respectively, and so the magnitude of continuation or extrapolation reflects the magnitude of momentum. The second type involves a lack of change (e.g., a previously reinforced behavior continues [i.e., not change] in the absence of any additional reinforcement until momentum of that behavior is dissipated [e.g., extinction occurs]). Both types of continuation or extrapolation involve a predicted future state, but in the first type, the future state involves continuation or extrapolation of a pattern of change, whereas in the second type, the future state involves continuation or extrapolation of a lack of change. This second type is not often discussed within the literature on dynamic approaches. The distinction between continuation or extrapolation involving change and continuation or extrapolation involving a lack of change maps loosely onto Hubbard's (2014, 2015a) distinction between momentum-like effects across space (usually involving change) and momentum-like effects across time (usually not involving change). Relatedly, momentum-like effects across space usually involve continuation or extrapolation of the action of a stimulus external to an observer, whereas momentum-like effects across time can involve continuation or extrapolation of the action of an observer or of a stimulus external to the observer.

Freyd's theory

Freyd's (1987) theory of dynamic representation was based on the single momentum-like effect of representational momentum. At the time Freyd's theory was published, only a few papers on behavioral momentum and psychological momentum had appeared, and the initial papers on operational momentum and attentional momentum had not yet appeared. Freyd suggested that dynamic mental representation intrinsically and necessarily represented time. The intrinsic property of temporal representation suggested that temporal information was directional (i.e., moved in only one direction) and continuous (i.e., between any two points in time, a third point could be identified). Evidence concerning directionality and continuity of representational momentum, operational

momentum, and attentional momentum is discussed in Hubbard (2014), and evidence concerning the directionality and continuity of behavioral momentum and psychological momentum is discussed in Hubbard (2015a). Continuation occurs across multiple time scales from milliseconds with representational momentum to potentially weeks, months, or longer with behavioral momentum (cf. Jordan, 2013; Jordan, Cialdella, Schloesser, & Bai, 2018). Importantly, if temporal information were not included, then all information might be represented as present or occurring simultaneously (i.e., not temporally ordered), and this would eliminate critical information. For example, without temporal ordering of information, conditioning would not be possible, as conditioned and unconditioned stimuli or responses could not be separated. Similarly, without temporal ordering of information, causal attributions would not be possible, as cause and effect could not be separated.

Freyd proposed several candidate properties for dynamic mental representation. As noted earlier, the first property of continuation was referred to as "the basic phenomenon" and involves continuation into a probable future state (e.g., forward displacement of the remembered final target location). Some of Freyd's candidate properties are specific to representational momentum or other momentum-like effects that occur on the time scale of perception (e.g., dynamic representation occurs very rapidly, increases over short retention intervals and then decreases), whereas other candidate properties appear more general and occur over longer time-scales (e.g., dynamic representation differs from guessing, is not due to purely sensory processes, depends upon a coherent direction of motion). Other candidate properties have been challenged by subsequent research (e.g., dynamic representation is not influenced by error feedback or learning). To the extent that operational momentum and attentional momentum are special cases of representational momentum, many of Freyd's candidate properties would apply to these other forms of momentum-like effect. However, several candidate properties do not seem applicable to momentum-like effects operating on longer time scales. Removal of candidate properties that do not characterize momentum-like effects operating on longer time scales might provide a list of potential properties for a more general theory of momentum-like effects, and this notion was the basis of Hubbard's (2014, 2015a, 2015b, 2017b) extension of Freyd's theory.

Hubbard's extension

Hubbard (2014, 2015a, 2015b, 2017b) examined whether Freyd's (1987) theory of dynamic representation, which was based on representational momentum, could be modified or extended to include other momentum-like effects. All momentum-like effects involve continuation of an action or process, and so Freyd's first property can be generalized to

other momentum-like effects. Similarly, momentum-like effects at longer time scales would not result from purely sensory effects, and so that property could also be generalized. Another property that generalizes is the importance of a coherent direction of motion. All momentum-like effects depend upon a specific and consistent direction of change. For example, if target direction or type is not consistent, representational momentum is disrupted (Kelly & Freyd, 1987; Kerzel, 2002); if the contingency between response and reinforcer is broken, behavioral momentum is disrupted (e.g., Nevin & Grace, 2000; Nevin & Shahan, 2011); and if a task is interrupted, psychological momentum is disrupted (e.g., Markman & Guenther, 2007). Freyd's suggestion that displacement increased with increases in velocity could be reframed as involving a more general rate of change rather than as velocity (i.e., momentum-like effects are larger with faster rates of change). Although Freyd suggested dynamic processes are impervious to error feedback or learning, subsequent findings regarding error feedback (Ruppel, Fleming, & Hubbard, 2009), expected changes in direction (Hubbard & Bharucha, 1988), semantic category of the target (Reed & Vinson, 1996), and expertise in the target domain (Blättler, Ferrari, Didierjean, & Marmèche, 2011), as well as effects of learning and experience on behavioral momentum (Nevin, 2015) and psychological momentum (Iso-Ahola & Dotson, 2014), suggest momentum-like effects can be influenced by error feedback or learning.

There are several reasons why a single more general dynamic mechanism for all types of momentum-like effects would be preferable to multiple (and presumably redundant) mechanisms, each of which was unique to a different type of momentum-like effect. First, a single more general mechanism could potentially bridge the gap between the isolated literature on each momentum-like effect; indeed, prior to Hubbard (2015a, 2015b), the literatures on representational momentum and behavioral momentum had no papers in common. Second, rather than positing multiple separate and unrelated (and redundant) mechanisms, a single (or smaller number of) more general mechanism(s) able to anticipate future actions or outcomes at multiple time scales is more parsimonious (cf. Hubbard, 2006b; Jordan, 2013; Jordan et al., 2018). Third, the idea of a more general dynamic representation that exhibits momentum-like effects provides specific predictions that can be tested (see Hubbard, 2015b, 2017b). Fourth, dynamic representation involves active processing and anticipation, and such an approach is consistent with developments in predictive processing (see below) and forward modeling (cf. Kawato, 1999; Pickering & Clark, 2014). Interestingly, many of the arguments for a single more general dynamic theory or model of momentum-like effects parallel arguments previously made within representational momentum literature for a more general

mechanism that could anticipate future positions of different types of stimuli (smoothly moving, implied motion, single frozen-action photographs), response methods (probe judgment, cursor positioning), and modalities (visual, auditory, tactile).

Other potential approaches

Hubbard's (2014, 2015a, 2015b, 2017b) extension of Freyd's (1987) theory made representational momentum the basis for developing a more general theory of momentum-like effects. However, there is no in principle reason why a theory underlying any other type of momentum-like effect could not be used as the basis for developing a more general theory of momentum-like effects. Different types of momentum-like effect have received different amounts of empirical investigation and theoretical development. There is insufficient theoretical development regarding operational momentum and attentional momentum to allow either of those to serve as a basis for developing a more general theory of momentum-like effects. There has been much more empirical investigation and theoretical development regarding behavioral momentum and psychological momentum, and it is possible that a theory underlying one of those effects could provide a basis for developing a more general theory of momentum-like effects. However, it is not clear how the constructs of learning theory used to explain behavioral momentum might be adapted to account for representational momentum, operational momentum, or attentional momentum, although it is possible that the more cognitively-oriented constructs underlying psychological momentum could be adapted. Indeed, it might be easier to move from cognitively-framed theories of momentum-like effects (e.g., representational momentum, psychological momentum) to behaviorally-framed theories of momentum-like effects (e.g., behavioral momentum) than to move from behaviorally-framed theories of momentum-like effects to cognitively-framed theories of momentum-like effects.

Rather than attempt a bottom-up theorizing in which properties and characteristics are potentially generalized from one type of momentum-like effect to another, it might be more useful to attempt a more top-down theorizing based on a general momentum metaphor. Such a top-down approach could address contributions of variables that arise directly from the momentum metaphor and thus should influence all momentum-like effects (e.g., velocity), as well as address contributions of variables that are more unique to specific types of momentum-like effect (e.g., resurgence, eye movements). Such an approach would be consistent with Marr's (1982) distinction between the levels of computational theory (i.e., what is the problem to be solved?), representation and algorithm (i.e., what set of rules can solve the problem?), and hardware implementation (i.e., how are those rules implemented?). As all momentum-like effects reflect an answer to

the problem of how to anticipate what might occur in the near future (i.e., how to interact with moving stimuli in real-time, what are the likely consequences of such interaction), all momentum-like effects could be viewed as equivalent at the level of computational theory (for discussion of computational theory and representational momentum, see Hubbard, 2005). Indeed, focusing on computational theory, rather than on differences in representations and algorithms or in hardware implementation, underscores the similarities between different momentum-like effects, and recognition of these similarities could aid the search for broader principles to potentially bridge between multiple momentum-like effects.

Toward a dynamic theory of momentum-like effects

If a general theory of momentum-like effects is to be developed, similarities and differences between different momentum-like effects and the variables that influence each type of momentum-like effect should be considered. Many of the similarities and differences between different types of momentum-like effect have been reviewed elsewhere (e.g., Hubbard, 2014, 2015a, 2015b, 2017b), and detailed discussion of potential constraints and consequences for an understanding of momentum-like effects suggested by those similarities and differences was presented in Hubbard (2015b, 2017b). Some of the constraints and consequences suggested by the existence of momentum-like effects and that are relevant for more general dynamic theories and models (and other predictive theories and models) are considered here, and these include the role of contingencies; bridging between gaps in perception, cognition, and action; adaptiveness of dynamic approaches; the influence of knowledge, beliefs, and expectations; and applications to naïve physics and perception of causality.

Contingencies

Momentum-like effects are influenced by environmental contingencies. For some momentum-like effects, these contingencies reflect invariant aspects of the environment (e.g., representational momentum might reflect invariant aspects of physical momentum). Although there has been considerable debate regarding whether physical principles have been internalized, and if so, whether that internalization involves dynamic information as well as geometric information (e.g., see the August 2001 Special Issue of *Behavioral and Brain Sciences*), the appearance of continuations and extrapolations that mimic effects of invariant physical principles is suggestive. Furthermore, momentum-like effects consistent with environmentally invariant information (regardless of the representational format) offer a potential bridge connecting Gibsonian

(ecological) approaches and representational approaches by positing that invariant information has shaped the sensitivity or the functional architecture of the representational system (see below). For other momentum-like effects, these contingencies reflect beliefs based on stochastic or arbitrary aspects of the environment that have been learned (e.g., behavioral momentum and psychological momentum reflect expectation of a certain outcome based on preceding actions). There is a potential continuum of contingency strength that involves the extent to which an action or process is invariant, stochastic, or arbitrary (cf. McBeath, 2018), and as suggested below, different levels of invariance might be related to whether the momentum-like effect of a given action or process is cognitively penetrable or cognitively impenetrable. In general, by anticipating contingencies, momentum-like effects offer a potentially adaptive mechanism or strategy for an individual's subsequent actions.

Bridging the gap

What advantage would dynamic representation have over other forms of representation? A compelling case could be made that dynamic information allows an individual to potentially fill in the gaps. At least two different types of gaps can be identified. The first type of gap is caused by delays in perception due to neural processing times, and this is a gap between perception and action. When a visually moving target is first sensed by the eye, that begins a sequence of sensory, perceptual, cognitive, and potential motor response processing. However, the target does not stop, pausing in place while waiting for the observer to finish this initial processing; rather, the target continues to move. By the time the initial processing is completed, the target has moved beyond the location where it was initially sensed. If the observer is to optimally interact with the target (e.g., catching, blocking, etc.), then any response to that target should be calibrated to where the target would be when the response would reach it and not where the target was when it was initially sensed. Representational momentum can help bridge this gap by helping to compensate for delays in neural processing time (Hubbard, 2005). The second type of gap is caused by failure of a learned response to be reinforced, and this is a gap between action and reinforcement. Presumably, it would not be optimal for a previously learned adaptive response to be immediately extinguished if a reinforcer is not presented on each trial (or each time the learned behavior should be executed), and behavioral momentum can bridge this gap by helping the response persevere until a reinforcer is presented, thus increasing latency to extinction (Nevin, 2015). Similarly, psychological momentum can potentially bridge between a previous action and a current or future action by suggesting a continuation of the previous action.

Adaptiveness

Haselton and Nettle (2006; Haselton, Bryant, Wilke, Frederick, Galperin, Frankenhuys, & Moore, 2009) suggest that biases evolve and are evolutionarily adaptive if judgments are made under conditions of uncertainty, if those judgments can impact evolutionary fitness, and if there is an asymmetric cost of false-positive errors and false-negative errors of those judgments. It could be argued that all of these conditions apply to at least some momentum-like effects. Moving physical targets are dynamic, and so representations of such targets need to capture that dynamic information. Momentum-like effects could be useful for anticipating the actions of a prey or predator (e.g., for a predator, underestimating the location of a prey could be more detrimental [prey escapes] than overestimating the location of a prey [predator waits]), and in cases of interception or avoidance, having an accurate real-time representation of the target would be adaptive in planning one's own actions. Furthermore, momentum-like effects are found in nonhuman animals (e.g., behavioral momentum in rats and pigeons, Cohen, Riley, & Weigle, 1993; data suggestive of representational momentum in pigeons, Neiwirth & Rilling, 1987). Representational momentum of an approaching target might be related to the looming bias (cf. Gray & Thornton, 2001), and the looming bias has been argued to increase evolutionary fitness (e.g., Neuhoff, 2018). Even so, it is not necessary that all examples of momentum-like effects are adaptive. For example, compelling cases for adaptiveness can be made for representational momentum (e.g., Hubbard, 2005) and behavioral momentum (e.g., Nevin, 2015), but it is not clear why operational momentum would be adaptive. In the latter case, it might be that operational momentum is a special case of representational momentum and was not detrimental enough to be selected against.

Knowledge, beliefs, and expectations

A critical element of any potential dynamic theory of momentum-like effects involves the extent to which such effects are influenced by an individual's knowledge, beliefs, and expectations. As discussed in Hubbard (2017b), there are at least three aspects of an individual's knowledge, beliefs, and expectations that should be considered, and these include whether such knowledge, beliefs, and expectations involve (a) cognitively penetrable or impenetrable processes, (b) variable or invariant properties (i.e., contingencies) of the environment, and (c) implicit or explicit processes.

Cognitively penetrable or impenetrable processes

Momentum-like effects involve both cognitively penetrable processes (that are influenced by knowledge, beliefs, and expectations), and cognitively impenetrable processes (that are not influenced by knowledge, beliefs, and expectations).

Some types of information influence momentum-like effects (e.g., physical target direction, Johnston & Jones, 2006; Verfaillie & d'Yewalle, 1991; feedback about one's performance, Kerick, Iso-Ahola, & Hatfield, 2000), but other types of information do not influence momentum-like effects (e.g., prior probabilities, Gilovich, Vallone, & Tversky, 1985; Hubbard & Lange, 2010). Semantic information regarding probable behavior (Hubbard, 1994) or target identity (Reed & Vinson, 1996) or importance (Markman & Guenther, 2007) influences momentum-like effects. The possibility that some types of information might be more or less likely to influence momentum-like effects might be related to McBeath's (2018) distinction between universal invariants and learned biological or cultural regularities, with cognitively impenetrable components related to universal invariants and cognitively penetrable components related to learned biological or cultural regularities. The distinction between cognitively penetrable and cognitively impenetrable processes maps onto the distinction between nonmodular and modular processes (cf. Fodor, 1983), respectively. The contributions of both types of processes to momentum-like effects suggests that momentum-like effects consist of at least two separate components, and this has implications for whether momentum-like processes can be minimized or maximized in training or treatment.

Variable or invariant properties Momentum-like effects are sensitive to knowledge or expectations derived from experience and beliefs regarding environmental contingencies. If experience of a specific stimulus type or exemplar is invariant (e.g., effects of momentum on physical objects), then momentum-like effects based on those contingencies are more likely to be consistent with physical and statistical laws. However, if experience of a specific stimulus type or exemplar is variable or if recent experience with that stimulus type or exemplar would constitute an outlier, then momentum-like effects based on those contingencies are more likely to be inconsistent with physical and statistical laws (e.g., belief in psychological momentum related to the hot hand effect is inconsistent with statistical laws, Hubbard, 2015a, 2015b); extrapolation of a momentum-like effect in the latter circumstances would suggest an atypical response or level of performance would continue, even though the response or level of performance should be expected to statistically regress. As suggested earlier, in order to be maximally efficient (e.g., not require additional processing resources), information regarding (or sensitivity to) invariants should be incorporated into the functional architecture of representation. It could be predicted that the stronger the invariance, the more likely that information has been incorporated into the functional architecture and less likely that other information (e.g., stimulus-specific beliefs) can modify the output (e.g., physical momentum is invariant, and so effects of physical momentum can be

modulated but not eliminated [e.g., the direction, but not the presence, of extrapolation can be influenced by other information, Finke & Freyd, 1989; Hubbard, 2005, 2006a]).

McBeath (2018) described three levels of potential invariance: strong universal invariants (e.g., effects of physical principles), intermediate biological motion or features (e.g., axis-aligned motion, forward-facing motion), and weak culturally learned regularities (e.g., driving on the right side of the road). As suggested earlier, universal invariants might contribute to a cognitively impenetrable process related to momentum-like effects, and weaker learned regularities might contribute to a cognitively penetrable process related to momentum-like effects. Furthermore, the presence of weakly learned constraints might allow use of a momentum metaphor in cases where there is no obvious relevant physical invariant involved (e.g., psychological momentum in sport competition), as the momentum-like effect in such circumstances might be driven entirely by cultural or other beliefs. Similarly, although momentum-like effects might involve impenetrability of some features of the environment (e.g., effects of momentum on physical objects reflected in representational momentum), there is clearly a larger penetrability of other features (e.g., learned behaviors reflected in behavioral momentum), and as noted earlier, it could be predicted that the degree of cognitive penetrability is inversely related to the strength of the invariant. Relatedly, Jordan et al. (2018) describe how actions constrain and contextualize subsequent perception, cognition, and action, and they suggest that information regarding universal invariants is reflected in the dynamic properties of our bodies and cognition, and so embodied cognition could be seen as reflecting the context within which our bodies evolved and are sustained.

The importance of both variable information and invariant information points toward a potential bridge between Gibsonian (ecological) approaches and representational approaches, in which invariant information produces an initial general effect that can then be modulated by variable (i.e., stimulus-specific) information reflecting the individual's knowledge, beliefs, and expectations (Hubbard, 2005, 2006a). More specifically, it is possible that environmentally invariant properties have shaped the properties of our representational system such that our representational system automatically initially picks up information related to those invariant properties (e.g., effects of momentum on moving physical objects, etc.) or that such information has already been incorporated into functional architecture of the representational system (perhaps in the form of higher-order isomorphism). This results in a momentum-like effect consistent with the emphasis on invariant properties of the environment in a Gibsonian (ecological) framework. The representation of this initial information can then be modified by stimulus-specific information (e.g., if an observer expects a specific moving object to accelerate, decelerate, or change direction). This ability to

modify the initial information via top-down internal processes is consistent with the effect of different expectations or knowledge in a representational framework. Such a view resolves apparent inconsistency between the Gibsonian (ecological) approach that perception is direct and representational approaches that perception is mediated by internal processes (cf. Philbeck & Witt, 2015; Witt & Riley, 2014), as each approach describes a different stage or process along the path of perception, cognition, and action.

Implicit or explicit processes Some momentum-like effects are influenced by explicit information (e.g., knowledge that an athlete rallied from a larger deficit to tie the score leads to reports of increased psychological momentum, Vallerand et al., 1988), whereas other momentum-like effects are not influenced by explicit information (e.g., knowledge of Newtonian physics does not influence representational momentum, Freyd & Jones, 1994; Kozhevnikov & Hegarty, 2001). In cases in which explicit information is not available, momentum-like effects might reflect implicit information. Thus, any theory of momentum-like effects would need to specify when explicit information would influence momentum-like effects and when implicit information would influence momentum-like effects. One possibility is that explicit information influences momentum-like effects as a function of the relevance of that information to the current task, but this possibility can be rejected, as highly relevant information can influence (e.g., object identity, Reed and Vinson, 1996) or not influence (e.g., Newtonian physics, Freyd & Jones, 1994; Kozhevnikov & Hegarty, 2001) momentum-like effects. A second possibility is that explicit information is more likely to influence momentum-like effects if that information involves variable characteristics rather than invariant characteristics of the action or process (as sensitivity to invariant information might be more likely to be incorporated into the functional architecture). How a distinction between implicit information and explicit information would apply in studies of momentum-like effects in nonhuman animals is not clear, however. Ultimately, a momentum-like effect might reflect implicit information, explicit information, or a combination of implicit information and explicit information.

Naïve physics and perception of causality

A role of naïve understanding of momentum is perhaps obvious in representational momentum, but such naïve understanding has also been suggested to operate in psychological momentum (e.g., Markman & Guenther, 2007) and in musical inertia (e.g., Larson, 2012). Such a role of naïve understanding of momentum in momentum-like effects is consistent with the broader notion that representational momentum reflects naïve understanding of the operation of physical systems and that such understanding might be generalized to other

types of stimuli. Literatures on naïve physics and on perception of causality focus on an individual's understanding of the functioning of simple physical systems, and given that momentum is a physical principle relevant to the operation of such systems, momentum-like effects could be related to or offer insight into naïve physics (e.g., Freyd & Jones, 1994; Kozhevnikov & Hegarty, 2001) and perception of causality (e.g., Hubbard, 2004, 2013a, 2013b, 2013c). However, neither literature on naïve physics nor literature on perception of causality has addressed the idea of momentum-like effects. Given that physical systems typically encountered in daily life are dynamic systems, it could be suggested that representation of those physical systems should be sensitive to the dynamics of those physical systems. Indeed, such a suggestion is consistent with findings that errors in judging the behavior of a physical system decrease when dynamic information (e.g., animation) is present (e.g., Kaiser, Proffitt, Whelan, & Hecht, 1992). Although the focus has been on momentum-like effects, effects based on sensitivity to (and perhaps naïve understanding of) other environmentally invariant physical principles (e.g., gravity, Hubbard, 1997, 2019; friction, Hubbard, 1995a; centripetal force, Hubbard, 1996) would be expected.

The encoding of dynamic information (or of information relevant to physical dynamics) does not necessarily have to reflect an accurate understanding or representation of those dynamics. Indeed, it could be argued that an inaccurate understanding that yielded a prediction or other result sufficient to allow survival, but that required less effort or resources to achieve, might be more optimal than a more accurate understanding that required more effort or resources to achieve. Naïve physics provides an example of this in naïve impetus theory (see McCloskey, 1983): When a moving object gives an initial push to a stationary object, the initially moving object is believed to impart an impetus to the initially stationary object, and this impetus is believed to dissipate with subsequent motion of the pushed object. The notion of impetus involves a single quantity, whereas a correct understanding of pushing involves consideration of multiple quantities (friction, mass, acceleration, etc.) and the relationships between these quantities; even so, the impetus notion yields a prediction that an object pushed into motion moves a short distance (farther if the pushing object moved faster or exhibited more

force) and then stops, and this is often sufficient. Thus, represented dynamics might not reflect correct physical laws, but would instead reflect heuristics based on subjective experience.² If “dynamic” is used in the first meaning (referring to change), then deviations between dynamics exhibited in representation and dynamics exhibited by physical objects would be of less concern; however, if “dynamic” is used in the second meaning (involving preservation of [information regarding] force), then deviations between dynamics exhibited in representation and dynamics exhibited by physical objects would be of more concern.

Implications of momentum-like effects for general dynamic approaches

Many of the constraints and consequences listed above regarding a dynamic approach to momentum-like effects also apply to more general dynamic approaches to perception, cognition and action. Additionally, there are a few other issues related to momentum-like effects that have implications for more general dynamic approaches, and these include clarifying the nature of “dynamic”; clarifying the differences between continuation, extrapolation, and change; perceptual inference of subjective rather than objective consequences; the importance of time scale and temporal information; identifying and discussing the computational theory level as well as the representation and algorithm level and the hardware implementation level; and momentum-like effects as an example of a predictive processing approach.

The nature of “dynamic”

Two different meanings of “dynamic” were suggested earlier, with one meaning based on the notion of change and another meaning based on the presence of (information regarding) force. However, studies involving dynamic approaches to perception, cognition, and action do not always explicitly address which meaning is intended. Many dynamic models and theories do not appear to explicitly define “dynamic”, although it appears that “dynamic” in the majority of papers is intended primarily in the first meaning rather than in the second meaning. Furthermore, each of those meanings has multiple senses; in the first meaning, the different senses refer to whether temporal information is viewed as an integral part of the representation, and in the second meaning, the different senses refer to whether (or how) information regarding force might be incorporated in the representation. The consideration of momentum-like effects has highlighted this issue, but specifying the intended meaning and sense of “dynamic” is critical for any theory or model that purports to use a dynamic approach, as different meanings and senses have different implications regarding properties and characteristics of the

² A related example can be seen in effects of implied mass on representational gravity (the tendency for judged location to be displaced in the direction of implied gravitational attraction, Hubbard, 1995b, 1997, 2005; Zago, 2018) and on representational momentum. Rather than reflecting objective mass of the target, the representation of the target appears to reflect weight rather than mass (e.g., on a horizontally moving target, mass influences displacement only along the axis aligned with gravitational attraction and not along the axis of motion). As gravity on the Earth's surface is not perceived to vary, distinguishing between weight and mass is often not necessary; indeed, the subjective effect of mass is weight, and so the functional architecture of the representational systems appears to incorporate information regarding subjectively experienced weight rather than information regarding objective mass *per se*.

representational system. Indeed, much as Miller (1962) suggested the word “consciousness” was a word worn smooth by a million tongues, so too the word “dynamic” is rapidly being worn smooth by the proliferation of articles purporting to use a dynamic approach or to contain a dynamic theory or model. However, just as with the word “consciousness”, it is not always clear what different investigators mean by the word “dynamic”.

Continuation, extrapolation, and change

There are at least two main issues involving continuation and extrapolation. The first issue is that different momentum-like effects involve different types of change. In some momentum-like effects, there is a change related to action (e.g., the remembered final location of a moving target is displaced forward in the direction of anticipated motion), but in other momentum-like effects, there is not a change related to action (e.g., a previously learned response continues to be emitted even if no reinforcement occurs). Even so, in all momentum-like effects there is anticipation of a near-future state. Just as this distinction between different types of change usefully distinguishes between different momentum-like effects, it is possible that consideration of such a distinction in the literature on dynamic approaches might provide useful information (e.g., dynamic theories or models that involve change might involve different properties or characteristics than do dynamic theories or models that do not involve change). A second issue involving continuation and extrapolation is the possible difference between continuation and extrapolation. As noted earlier, “continuation” and “extrapolation” appear to be used interchangeably in the literature, although “continuation” connotes a more passive process and “extrapolation” connotes a more active process. One suggestion is that “continuation” be used to refer to the initial (default) effect when no other information about the stimulus is present, and that “extrapolation” be used to refer to a more active (but automatic) potential modulation of the initial (default) effect by stimulus-specific knowledge (e.g., target identity, expected change of direction, etc.). The actual observed effect could then reflect a continuation or reflect a continuation and subsequent extrapolation.

Perceptual inference

The existence of momentum-like effects involving continuation and extrapolation suggests that perception, cognition, and action are adjusted to fit an expected future state. Such adjustment to an expected state is not a new idea, but has several antecedents in the literature (e.g., Helmholtz, 1860/1962, and Rock, 1983, suggested perception was influenced by inferences regarding the most probable stimulus). Momentum-like effects are also consistent with notions regarding mental models (e.g., Johnson-Laird, 1983) and mental simulations of

physical systems (e.g., Hegarty, 2004) or other dynamic processes (e.g., Grinblatt & Han, 2005). However, studies of momentum-like effects suggest that the dynamics represented by a cognitive system do not necessarily accurately reflect the objective dynamics of the referent stimulus or situation, and this provides an important constraint on considerations of the dynamics of perception, cognition, and action. More specifically, the dynamics represented by a cognitive system appear to reflect the anticipated subjective consequences for an observer (e.g., dynamics regarding objective mass might be represented by subjective experience of weight, Hubbard, 1997, 2019). Displacement of computer-animated targets in studies of representational momentum, exhibited behavior in studies of behavioral momentum, and subjective feeling in studies of psychological momentum typically do not contain stimuli that would experience or exhibit objective physical momentum; rather, the experienced momentum-like effect involves subjective consequences of the action or process for the observer. Another example involves the recent increase in interest in action-specific perception (in which a person’s anticipated actions influence his or her perception [e.g., of ball size, hill slope, etc.]; see Philbeck & Witt, 2015; Witt, 2018), as action-specific perception suggests that inferences related to dynamics of anticipated action influence current perception.

Time scale and temporal information

Continuation and extrapolation can occur at multiple time scales, and so there have been calls for more general dynamic models that could operate at multiple time scales (e.g., Jordan, 2013; Jordan et al., 2018; Schöner et al., 2016), and as noted earlier, different forms of momentum-like effect operate at different time scales. As also noted earlier, momentum-like processes that operate at the time scale of perception appear to involve effects primarily across space, whereas momentum-like processes that operate at longer time scales appear to involve effects primarily across time. This suggests that dynamic theories or models that operate at different time scales might emphasize different aspects of the stimulus or the response. The importance of temporal information and time scale is not a new idea, though. An emphasis on changes in time is central to Freyd’s (1987) observation that temporal information is a critical but often overlooked element of psychological theorizing and Jones’s (1976) characterization of time as a “lost dimension” in psychological studies. Indeed, Freyd discussed how empirical findings typically interpreted as demonstrating the importance of spatial information in mental representation (e.g. results from studies on mental rotation) could be easily interpreted as demonstrating the importance of temporal information, and Jones (1976) stressed the importance of temporal (and specifically rhythmic) information at a variety of time scales and for a variety of phenomena.

Specifically, Jones stressed the importance of serial integrity, and this is consistent with a critical aspect of dynamic approaches to momentum-like effects, namely, that time and temporal order are necessary and intrinsic features of mental representation (see also Jones & Boltz, 1989).

Importance of the computational theory

Although dynamic theories or models might offer good matches to empirical or simulated data, how such theories or models fit within the larger domains of perception, cognition, and action is not always addressed. Many dynamic approaches to perception, cognition, and action are focused, often entirely so, at the representation and algorithm level or at the hardware implementation level. Even though these theories and models are often strongly computational, they do not address the computational level.³ In Marr's view, focusing on mechanisms (i.e., on the level of representation and algorithm or on the level of hardware implementation) without considering the problem to be solved would be like trying to understand the principles of flight by focusing solely on the structure of a feather (and thus other or more abstract principles not specifically related to feathers might be missed). Additionally, as the problem to be solved often involves properties of the environment or properties of objects in the environment, the computational theory level emphasizes environmental (ecological) inputs and how such inputs (e.g., contingencies) influence or constrain the other levels. For example, in the case of momentum-like effects, the possibility of a single theory or model of all momentum-like effects was grounded in a computational theory level (i.e., the momentum-like effects offered a solution to how an individual could anticipate the near future and bridge the gaps between perception and action and between action and reinforcement) that addresses potential future theories and models and addresses how momentum-like effects fit into the larger domains of perception, cognition, and action.

Predictive processing

Momentum-like effects reflect continuation and extrapolation regarding the likely state of an action or process in the near future, and such effects can be considered a type of predictive processing. Just as predictive processing involves top-down effects that influence the content of the representation (cf. hierarchical predictive coding, Lee & Mumford, 2003; Rao & Bullard, 1999), momentum-like effects involve top-down

effects of expectancy and previous knowledge (Hubbard, 2015b). Just as goals of predictive processing include production of movements that reduce the error between perception and action (Friston, 2003) and increase the amount of energy available to do work (i.e., “a free energy formulation”, Friston, 2010), a goal of momentum-like effects is to increase the accuracy and efficiency of interaction with stimuli (thus reducing errors and saving energy). Just as predictive processing involves relationships between sensory or motor data and probable real-world sources (Hohwy, 2007), so too do momentum-like effects (and more generally, any bias in representation attributed to effects of invariant physical principles) involve the relationship between sensory or motor data and real-world sources (Hubbard, 2005). Also, predictive processing (Clark, 2013) and momentum-like effects (Hubbard, 2015b, 2017b) each operate at multiple time scales. Indeed, in reviewing predictive processing, Bendixen, SanMiguel, and Schröger (2012, p.129) suggest predictive processing “automatically leads to a coherent perceptual impression, and it helps in anticipating the movement's continuation (which, in turn, allows for the adaptation of own [sic] motor acts)”, and this suggestion is equally consistent with momentum-like effects. However, discussions of predictive processing have not typically considered momentum-like effects.

A consideration of momentum-like effects suggests there are at least two levels of processing (involving invariant principles and stimulus-specific information, Hubbard, 2006a), and these seem compatible with two levels suggested for predictive processing (involving units that code representational content and units that code predictive error, de-Wit et al., 2010; Friston, 2005). One level involves a general shift in the direction of expected movement or change and corrects for potential error. Information regarding effects of momentum could act as a Bayesian prior for lower-level processing,⁴ because the probability that a moving or changing physical object would be influenced by momentum is extremely high. Just as many illusions occur because of strategies that are otherwise optimal under everyday conditions (Weiss et al., 2002), momentum-like effects occur as a result of strategies that are optimal under everyday conditions (consistent with this, representational momentum has been considered as an illusion, Roediger, 1996). A second level is due to stimulus specific knowledge (e.g., object type, expected change in behavior, etc.) and representational content that can modulate the first level. The existence of this second level has been shown in studies of dynamic predictive coding in which neural systems change their response as a function of changing image statistics (e.g., Hosoya et al., 2005) and effects of context, expectations, and knowledge on momentum-like effects

³ Marr's (1982) choice of the term “computational level” for the level of understanding that involved what question some perceptual, cognitive, or behavioral process would solve is perhaps unfortunate, as “computation” is usually associated more with algorithms and implementation strategies. Perhaps ironically, the “computational level” potentially involves the least computation per se of any of Marr's three levels.

⁴ Consistent with this, another invariant physical principle, gravity, has recently been suggested to function as a strong Bayesian prior (Jörges & López-Moliner, 2017).

(e.g., Hubbard, 2015b, 2017b). Momentum-like effects influence the perception of the self or any external stimulus, as well as the actions toward or by the self or by an external stimulus, and thus offer a still relatively untapped source of information regarding the dynamics of perception, cognition, and action and of action-oriented predictive processing.

Summary and conclusions

There are many different forms of momentum-like effects, and these differ in the action or process that is continued or extrapolated and in the time scale of that continuation or extrapolation. Momentum-like effects have typically not been widely discussed within the larger literature involving dynamic approaches in perception, cognition, and action, but such effects provide clear examples of dynamic processes and raise issues that are important in the study of other dynamic processes. One issue is whether “dynamic” is defined in a colloquial sense as involving change or in a technical sense as involving force. Both of these definitions stress the importance of temporal information and how temporal information is represented. A second issue involves the continuation or extrapolation that is produced by dynamic processes. Consideration of different momentum-like effects underscores differences between continuation or extrapolation involving change and continuation or extrapolation that does not involve change, and this is a distinction not generally addressed within the larger literature on dynamic approaches. Attempts to develop a general dynamic approach to momentum-like effects based on an early theory of representational momentum underscored the importance of considering the computational theory level; however, issues of the computational theory level are not generally addressed within the larger literature on dynamic approaches, which tends to focus on algorithms and implementations (e.g., modeling). Momentum-like effects share many properties with predictive processing theories and models of perception, cognition, and action, and offer important considerations for future empirical studies and theoretical development.

Constraints on and consequences of potential dynamic approaches to momentum-like effects involve consideration of the nature and different types of contingencies, as well as consideration of the extent to which different contingencies reflect variable or invariant information. The role of momentum-like effects in bridging gaps between perception and action and between action and reinforcement, and the potential adaptiveness of such bridging, further underscores the importance of the computational theory level for dynamic approaches. The influence of an individual’s knowledge, beliefs, and expectations on momentum-like effects highlights a number of issues that should be considered by dynamic approaches, including the extent to which dynamic processes are

cognitively impenetrable (modular) or cognitively penetrable (nonmodular), whether inputs to those processes are variable or invariant, and whether inputs to those process involve explicit information or implicit information. In all these cases, determining the conditions under which different types of information influence a dynamic process is important, but not all of these issues are usually addressed by broader dynamic approaches. Additional implications of momentum-like effects of dynamic approaches include distinguishing between continuation and extrapolation (and other processes that might be involved) and considering different time scales. Overall, momentum-like effects provide a useful example of a relatively simple dynamic process that reveals and highlights multiple issues relevant for broader or more general dynamic approaches to other phenomena in perception, cognition, and action.

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