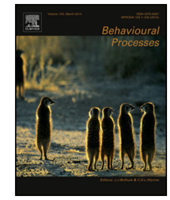
Behavioural Processes 141 (2017) 50–66

Contents lists available at ScienceDirect

Behavioural Processes

journal homepage: www.elsevier.com/locate/behavproc



Toward a general theory of momentum-like effects

Timothy L. Hubbard

Arizona State University

ARTICLE INFO

Article history:
Received 11 November 2016
Received in revised form 19 February 2017
Accepted 20 February 2017
Available online 28 February 2017

Keywords:
Representational momentum
Operational momentum
Attentional momentum
Behavioral momentum
Psychological momentum
Dynamic representation

ABSTRACT

The future actions, behaviors, and outcomes of objects, individuals, and processes can often be anticipated, and some of these anticipations have been hypothesized to result from momentum-like effects. Five types of momentum-like effects (representational momentum, operational momentum, attentional momentum, behavioral momentum, psychological momentum) are briefly described. Potential similarities involving properties of momentum-like effects (continuation, coherence, role of chance or guessing, role of sensory processing, imperviousness to practice or error feedback, shifts in memory for position, effects of changes in velocity, rapid occurrence, effects of retention interval, attachment to an object rather than an abstract frame of reference, nonrigid transformation) are described, and potential constraints on a future theory of momentum-like effects (dynamic representation, nature of extrapolation, sensitivity to environmental contingencies, bridging gaps between stimulus and response, increasing adaptiveness to the environment, serving as a heuristic for perception and action, insensitivity to stimulus format, importance of subjective consequences, role of knowledge and belief, automaticity of occurrence, properties of functional architecture) are discussed. The similarity and ubiquity of momentum-like effects suggests such effects might result from a single or small number of mechanisms that operate over different dimensions, modalities, and time-scales and provide a fundamental adaptation for perception and action.

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E-mail address: timothyleehubbard@gmail.com

http://dx.doi.org/10.1016/j.beproc.2017.02.019
0376-6357/

1. Introduction

People and nonhuman animals can often anticipate the future actions, behaviors, and outcomes of objects, individuals, and processes, and some of these anticipations have been hypothesized to result from momentum-like effects. There are at least five types of momentum-like effects that have been proposed, and these operate on a variety of stimulus dimensions, modalities, and time-scales and include representational momentum, operational momentum, attentional momentum, behavioral momentum, and psychological momentum (Hubbard, 2015b). Literature on each of these momentum-like effects has typically been isolated from literatures on other momentum-like effects. The most well-known and most-studied examples of momentum-like effects are behavioral momentum and representational momentum. Perhaps surprisingly, even though the first paper on behavioral momentum was published in 1983 (Nevin et al., 1983), and the first paper on representational momentum was published in 1984 (Freyd and Finke, 1984), these two effects were not discussed in the same paper until 2015 (Hubbard, 2015b). The primary purpose here is to provide a brief overview of different momentum-like effects, consider similarities of the properties of different momentum-like effects, and propose constraints relevant to any future theory of momentum-like effects. Such a consideration should suggest multiple potential avenues for empirical investigation and potential theoretical connections between different momentum-like effects.

2. Varieties of momentum-like effects

As suggested in Hubbard (2014, 2015a,b) there are at least two different groups of momentum-like effects. One group involves effects that occur on a perceptual time-scale and subjectively involve extrapolation primarily across space, and a second group involves effects that occur on a longer time-scale and subjectively involve extrapolation primarily across time. These are briefly described here, and more detailed reviews and discussion are provided in Hubbard (2014, 2015a,b).

2.1. Perceptual time-scale

There are at least three types of momentum-like effect that involve a perceptual time-scale, and these include representational momentum, operational momentum, and attentional momentum.

2.1.1. Representational momentum

If an observer views a moving target and subsequently indicates the remembered final location of that target, the judged final location is usually displaced from the actual final location in the direction of anticipated motion (i.e., the target is judged as traveling slightly farther than it actually traveled). This displacement has been referred to as *representational momentum* (Freyd and Finke, 1984; see reviews in Hubbard, 1995b, 2005, 2014). Representational momentum can be induced with targets that exhibit smooth continuous motion (e.g., a small geometric shape moving across a display, Hubbard and Bharucha, 1988), exhibit implied discrete motion (e.g., a sequential series of static rectangles at different orientations that imply rotation in a consistent direction, Freyd and Finke, 1984), or consist of a single frozen-action stimulus (i.e., a static image that implies motion in a specific direction, e.g., a photograph of person walking in a specific direction, Futterweit and Beilin, 1994). Representational momentum has been assessed with response measures such as cursor-positioning (e.g., placing the cursor beyond the actual final position when indicating judged final location, Hubbard and Bharucha, 1988), comparison of the remembered final target location with the location of a subsequently presented probe (e.g., a higher likelihood that probes beyond the actual final location than probes behind the actual final location will be judged the same as the final target location, Freyd and Finke, 1984), or touching the display (e.g., touching a location slightly beyond the actual final location, Ashida, 2004). Several theories of representational momentum are discussed in Hubbard (2010).

2.1.2. Operational momentum

If an individual makes a rapid estimate of the sum or difference of two quantities, he or she is likely to overestimate the sum and underestimate the difference (i.e., the estimated sum is larger than the actual sum and the estimated difference is smaller than the actual difference [e.g., a participant asked to mentally add a cluster of 8 dots to a cluster of 24 dots is more likely to judge a cluster of more than 32 dots as correct, and a participant asked to mentally subtract a cluster of 8 dots from a cluster of 24 dots is more likely to judge a cluster of less than 16 dots as correct]). This has been referred to as *operational momentum* (McCrink et al., 2007). Operational momentum occurs with symbolic indicators of quantity such as Arabic numerals and equations (e.g., Knops et al., 2013; Lindemann and Tira, 2011), non-symbolic indicators of quantity such as dot clusters (e.g., McCrink et al., 2007), and pointing to a location along a line (e.g., Pinhas and Fischer, 2008). Just as representational momentum reflects motion in physical space, operational momentum has been posited to reflect motion in numeric space; indeed, one hypothesis is that operational momentum reflects representational momentum for movement in the direction of the arithmetic operator (rightward for addition and leftward for subtraction) along a mental number line (McCrink et al., 2007). Other theories of operational momentum include attentional shifts due to the interplay of different cortical structures that process spatial information (e.g., Knops et al., 2009) and a general heuristic to accept larger quantities if adding and smaller quantities if subtracting (e.g., McCrink and Wynn, 2009).

2.1.3. Attentional momentum

If attention is being returned to a specified fixation point after an exogenous cue that diverted attention to another location was presented, then participants are faster to detect a subsequent target that lies further ahead in the same direction as the current movement of attention than to detect a target that is an equal distance away in some other direction. This has been referred to as *attentional momentum* (Pratt et al., 1999), and the differences in detection times have been attributed to a momentum inherent in the shifting of attention across space. Because of this momentum, more time is required to stop the movement of attention in a given direction and begin movement in a different direction than to continue movement of attention in the same direction. There have been attempts to relate attentional momentum to inhibition of return, but the data are mixed (cf. Snyder et al., 2001, 2009; Spalek and Hammad, 2004). Interestingly, attentional momentum might also be related to movement of (and representational momentum for) a physical target, as response time to detect whether a specific feature is present on a probe stimulus is decreased if that probe is presented slightly in front of the final location of a previously viewed moving target (i.e., located where representational momentum suggests the target would be) than if that probe is presented slightly behind the final location of a previously viewed moving target (Kerzel et al., 2001).

2.2. Longer time-scale

There are at least two types of momentum-like effect that involve a longer time-scale, and these include behavioral momentum and psychological momentum.[1]

2.2.1. Behavioral momentum

If an individual receives a consistent rate of reinforcement for a given behavior, then that behavior is likely to continue. In other words, 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 a new variable or a current variable is discontinued. This has been referred to as *behavioral momentum* (Nevin, 2015; Nevin et al., 1983). Unlike other momentum-like effects, behavioral momentum is firmly grounded in a rigorous mathematical framework (e.g., Nevin, 1992; Nevin and Shahan, 2011). Behavioral momentum has typically been studied in nonhuman animals within the context of learning theory (e.g., Nevin and Grace, 2000; Nevin and Shahan, 2011) or in humans diagnosed with developmental disorders or psychopathology (e.g., Dube et al., 2009). In a typical animal study of behavioral momentum, laboratory animals on multiple variable interval schedules are provided with food reinforcement (e.g., Nevin et al., 1983). Additional noncontingent reinforcement is sometimes also delivered (e.g., Nevin et al., 1990). Resistance to disruptors (e.g. extinction, prefeeding, alternative reinforcement) is higher if training reinforcement rate is higher or if additional noncontingent reinforcement is also presented. In a typical human study of behavioral momentum, increases in reinforcement of desired behaviors, and increases in compliance with instructed behaviors, increases resistance to extinction or to other disruption of the desired behavior (e.g., Parry-Cruwys et al., 2011).

2.2.2. Psychological momentum

Whether an individual experienced success or failure at a given task in the recent past is often believed to influence the likelihood of success or failure on a similar task in the present or in the near future. In other words, perception of whether a potential action or outcome (e.g., scoring on the next shot, winning the current game) is more or less easily achieved is influenced by the success or failure of previous actions or outcomes (e.g., scoring on the previous shot, winning the previous game). This is referred to as *psychological momentum* (Iso-Ahola and Mobily, 1980; Vallerand et al., 1988). Psychological momentum can be positive (current success or victory is believed to increase the likelihood of subsequent success or victory) or negative (current failure or defeat is believed to increase the likelihood of subsequent failure or defeat). In a typical study of psychological momentum, a participant views (e.g., Silva et al., 1988) or competes against (e.g., Shaw et al., 1992) another individual in a task or game, and verbal reports of momentum perceived by the participant or attributed to the other individual by the participant are collected. Other studies broadened the notion of psychological momentum beyond sport or game competition (e.g., Arkes, 2011; Hendricks et al., 1993; Markman and Guenther, 2007). Several theories of psychological momentum have been proposed (e.g., Adler, 1981; Cornelius et al., 1997; Iso-Ahola & Dotson, 2014, 2016; Markman & Guenther, 2007; Taylor & Demick, 1994; Vallerand et al., 1988).

3. Similarities of momentum-like effects

The forms of momentum-like effect discussed in Section 2 seem quite different, and the most obvious similarity of different momentum-like effects is an inclusion of the word "momentum" in their names. However, if momentum-like effects are actually based on a form of momentum, then it should be possible to identify analogues of each of the components of physical momentum for each type of momentum-like effect, find similarities in the effects of a given variable on different momentum-like effects, and find similarities in the properties exhibited by different momentum-like effects.

3.1. Components

Physical momentum is the product of an object's mass and velocity. If momentum-like effects are based on momentum, then it should be possible to identify the analogues or equivalents of mass and velocity for each type of momentum-like effect. In representational momentum, the analogue of velocity is target velocity, and Hubbard (1997) suggested the analogue of mass is target weight (i.e., the subjective experience of mass by organisms on Earth's surface). The analogues of mass and velocity for operational momentum or for attentional momentum have not been specified in the literature, but Hubbard (2015b) suggested the size of the operands and velocity along the number line as potential analogues for operational momentum and the width of the attentional lens or spotlight and velocity of the shift of attention across space as potential analogues for attentional momentum. Nevin (1988, 2012) suggested the analogues of mass and velocity in behavioral

[1] Whether momentum-like effects in musical stimuli reflect representational momentum, behavioral momentum, or psychological momentum, or whether such effects reflect a unique type of musical momentum, is considered in Hubbard (2017).

momentum were resistance to change in behavior and response rate, respectively. Markman and Guenther (2007) suggested the analogues of mass and velocity in psychological momentum were the importance of the task or goal and reinforcement rate, respectively. The key point is that mass and velocity analogues can be specified and are independent (as are mass and velocity in physical momentum) for each type of momentum-like effect (but see Nevin et al., 2001). Because momentum-like effects occur with a variety of stimulus dimensions, modalities, and time scales, whether those analogues differ across varieties of momentum-like effect is less important than whether such analogues can be identified.

3.2. Variables

If different types of momentum-like effect involve similar mechanisms or result from a more general mechanism (cf. Hubbard, 2005, 2006a,b) that can operate at multiple time-scales (cf. Hubbard, 2015b; Jordan, 2013), then variables that influence one type of momentum-like effect should have similar effects on other types of momentum-like effect (e.g., if increases in velocity or rate of change result in a larger effect for one type of momentum-like effect, then increases in velocity or rate of change should result in a larger effect for other types of momentum-like effects). Of course, the presence of such similarities is consistent with, but does not conclusively demonstrate, the existence of a single mechanism; even so, considerations of parsimony suggest a single mechanism might be more likely. However, only a limited number of comparisons are possible, as many variables that have been examined for one type of momentum-like effect have not yet been examined for other types of momentum-like effect. Specific variables for which similar effects have been found for at least two different momentum-like effects include velocity (rate of change), distance/duration, direction, size/mass, identity, valence, format, retention interval, contrast, configuration, expectations, prior probability, attention, age, practice and error feedback, expertise, control over the target, goal pursuit, and psychopathology. As this information has been recently reviewed in detail elsewhere (Hubbard, 2014, 2015a,b), a full review is not repeated here, but as a convenience, the effects of these variables on momentum-like effects are summarized in Table 1.

3.3. Properties

If different types of momentum-like effect involve similar mechanisms or result from a more general mechanism that can operate at multiple time-scales, then properties of one type of momentum-like effect should be similar to properties of other types of momentum-like effect. Freyd (1987) listed several properties of representational momentum, but that discussion did not address properties of other types of momentum-like effect. Hubbard (2015a) discussed how Freyd's list might be modified to include behavioral momentum and psychological momentum. A more detailed and comprehensive consideration including a greater range of momentum-like effects is presented here, and properties addressed here include continuation, coherence (consistency), the potential role of chance or guessing, the potential role of sensory processing, imperviousness to practice or error feedback, shifts in memory for position, effects of changes in velocity (rate of change), rapid occurrence, effects of retention interval, attachment to an object rather than to an abstract frame of reference, and the possibility of changes other than rigid visual transformation.

3.3.1. Continuation

Momentum-like effects continue the current behavior of the stimulus, and Freyd (1987) considered representational momentum as an example of this property of continuation. In the case of representational momentum, the representation of a target consistently changing in location, orientation, shape, or any other continuous dimension is displaced (continued) in the direction of that change (e.g., if an object was rotating, then the representation of that object's orientation was shifted slightly further in the direction of rotation). In operational momentum, the action of addition or subtraction involves movement through numerical space (e.g., perhaps along a mental number line), and motion is continued beyond the actual sum or difference. In attentional momentum, continuation involves movement of the fixation of attention in an unchanging direction across physical space. In behavioral momentum and in psychological momentum, continuation involves a repetition or extension of the same behavior (i.e., a resistance to extinction of the current behavior). Thus, in all momentum-like effects, the current action, behavior, or outcome is extrapolated to continue into the future. Freyd (1987) suggested continuation (referred to as "the basic phenomenon") was a characteristic of dynamic representation; however, continuation is also a property of momentum-like effects by definition, as such effects are defined or described as involving extrapolation of the future action, behavior, or outcome of a target, person, or process.

3.3.2. Coherence

The direction of an action, behavior, or process (i.e., change) must be consistent, or in Freyd's (1987) term, coherent, if a momentum-like effect is to occur. For representational momentum along any dimension of change to occur, changes in the stimulus must occur in a consistent manner (e.g., a target rotating in a clockwise direction). A sequence of random (or at least unpredictable) changes along a given dimension of the stimulus would not result in representational momentum for the changing dimension (e.g. random changes in direction of motion would not lead to expectation of continuation in a single specific direction). Coherence has not been addressed for operational momentum or attentional momentum, but presumably the shift of attention through numeric space (in operational momentum) or through physical space (in attentional momentum) would be in a consistent direction and would not involve random shifts in direction. Indeed, a shift in an incoherent direction (i.e., different from preceding motion) would correspond to a different arithmetic operation (in operational momentum) and to an increased response time (in attentional momentum). In the cases of representational momentum, operational momentum, and attentional momentum, the notion of coherence describes a property of the target and does not depend upon the observer's response to the target or on any reinforcement of the observer's response.

Coherence is less easily defined in behavioral momentum. It might initially appear that consistently reinforcing a specific target behavior and not reinforcing an opposite or incompatible behavior would be analogous to coherent motion, and that reinforcing both a specific target behavior and an opposite or incompatible behavior would be analogous to incoherent motion. However, behavioral momentum for a target behavior can be increased by the presence of additional noncontingent reinforcement or reinforcement for other behaviors in the same context, as well as by the presence of reinforcement for the target behavior (e.g., Bai et al., 2016; Nevin et al., 1990; Nevin et al., 2016), and this suggests coherence might be a property of not just the target, but is instead a property of the larger target and environment system (cf. regulatory control of behavior in cybernetics, Ashby, 1956/2015; Wiener, 1961/2013). Such a view might predict that as long as reinforcement specifically for the target behavior was a sufficient proportion of the total reinforcement, behavioral momentum for the target behavior would be maintained. Whether coherence in psychological momentum is similarly dependent on reinforcement for just the target behavior or reinforcement for the target behavior in combination with

Table 1
Primary Influences of Different Variables on Momentum-Like Effects.

Variable	RM	OM	AM	BM	PM
Velocity	Increases with faster constant velocities (Hubbard and Bharucha, 1988), increases and decreases with acceleration and deceleration, respectively (Finke et al., 1986)	?	?	Increases with increases in response rate (Nevin et al., 1983), decreases with withdrawal of reinforcement (Nevin and Shahan, 2011), decreases with increases in response rate if reinforcement rate is constant (Nevin et al., 2001)	Increases and decreases with increases and deceases, respectively, in reinforcement (Mace et al., 1992)
Distance/Duration	Typically no effect (de sá Teixeira and Oliveira, 2011), but proximity to edge (Hubbard and Motes, 2005), source of motion (Hubbard and Ruppel, 2002) and pathology (McGeorge et al., 2006) can influence	Increases if the second operand is zero (Pinhas and Fischer, 2008)	Increases if the cue is farther, or the target closer, to fixation (Pratt et al., 1999)	Different schedules should be compared within the same session (Cohen, 1998)	Increases with increasing success (Hunt et al., 2013), can be terminated by interrupting the task (Mace et al., 1992) or unsuccessful performance (Briki et al., 2014b)
Direction	Larger for horizontal than vertical motion and for descending than ascending motion (Hubbard, 1990)	Larger for subtraction (leftward motion along number line) than addition (Knops et al., 2009)	Larger for downward or rightward motion (Spalek and Hammad, 2004)	More likely in current direction of behavior (Silva et al., 1988)	More likely in current direction of behavior (Silva et al., 1988), negative might be stronger than positive (Gernigon et al., 2010)
Size/Mass	Larger displacement along gravity axis for larger targets (Hubbard, 1997)	Not influenced by whether operands are single or double digits (Knops et al., 2009)	?	Increases with increases in behavioral mass (Nevin, 1988), continuous reinforcement larger than partial reinforcement (Nevin, 2012)	Larger for more important tasks (Markman and Guenther, 2007)
Identity	Disrupted if constant target identity is not maintained (Kelly and Freyd, 1987), influenced by semantic category of the target (Reed and Vinson, 1996)	Decreases if operands are the same (Charras et al., 2014)	?	Increases with preferred reinforcers (Mace et al., 1997)	Larger effects for more important tasks (Markman and Guenther, 2007)
Valence	Larger for targets labeled as threatening (Greenstein et al., 2016) or when motion is congruent with painful contact (Hudson et al., 2016)	?	?	More resistant to extinction following higher quality reinforcers (Ahearn et al., 2003)	Effects congruent with valence are more common than effects incongruent with valence (Silva et al., 1988), negative PM is stronger than positive PM (Gernigon et al., 2010)
Format	Occurs with implied motion (Freyd and Finke, 1984), continuous motion (Hubbard and Bharucha, 1988), and static frozen action stimuli (Futterweit and Beilin, 1994)	Occurs with dot clusters (McCrink et al., 2007), Arabic numerals (Knops et al., 2009), and pointing to a line (Pinhas and Fischer, 2008)	?	Occurs with wide range of stimuli and reinforcers (Hubbard, 2015a)	Occurs with wide range of stimuli and reinforcers (Hubbard, 2015a)

Retention Interval	Peaks within a few hundred milliseconds and declines (Freyd and Johnson, 1987)	?	Found after 600 but not 1200 milliseconds (Samuel and Kat, 2003)	Increases within a session (Cohen et al., 1993), can potentially last for years (Nevin, 1996)	Decreases as temporal interval increases (Eisler and Spink, 1998), increases rapidly before becoming stable (Briki et al., 2014b)
Contrast	Increases if contrast with background is high or increasing (Hubbard and Ruppel, 2014)	?	?	Sensitivity to differences between multiple reinforcement schedules (Cohen, 1998; Nevin, 1988), whether behaviors are high or low probability (Ardoin et al., 1999)	Increases if a player rallies from larger deficit (Vallerand et al., 1988)
Configuration	Increases if nearby context moves in the same direction as target (Hubbard, 1993), decreases if target motion is imparted from another stimuli (Hubbard et al., 2001), can experience resistance analogous to friction (Hubbard, 1995a)	?	Increases with increases in the change of direction of attentional shift (Pratt et al., 1999)	Previous compliance with high probability request increases subsequent compliance with low probability request (Belfiore et al., 2008), can experience resistance analogous to friction (Nevin, 1988)	Larger if prior context contained more reinforcement (Mace et al., 1992), increases if a player rallies from larger deficit (Vallerand et al., 1988)
Expectations	In the direction of expected rather than actual motion (Hubbard and Bharucha, 1988)	?	?	Increases with richer reinforcement (Podlesnik et al., 2012a; Podlesnik et al., 2012b) or noncontingent reinforcer (Nevin et al., 1990)	Is influenced by one's own or one's opponent's behavior (Briki et al., 2014a), increases for teams with high cohesion (Eisler and Spink, 1998)
Prior Probability	Increases in likelihood of a *same* response with increases in actual or perceived likelihood a *same* response would be correct (Hubbard and Lange, 2010)	?	?	Previous compliance with high probability request increases subsequent compliance with low probability request (Ardoin et al., 1999; Mace and Belfiore, 1990)	Winning or scoring is believed to make subsequent winning or scoring more likely (e.g., the hot hand effect (Gilovich et al., 1985)
Attention	Increases under divided attention (Hayes and Freyd, 2002), increases if target is cued (Hubbard et al., 2009)	Increases under divided attention (McCrink and Hubbard, in press), addition and subtraction facilitates target detection in right and left visual field, respectively (Masson and Pesenti, 2014)	Detection of probe in front of moving target is facilitated (Kerzel et al., 2001)	Occurs with selective (Dube et al., 2003) and divided (Podlesnik et al., 2012a,b) attention, larger with multiple schedules than a single schedule (Podlesnik et al., 2012a,b), effect of rate of reinforcement in multiple but not simple schedules (Cohen et al., 1993)	Is disrupted if performance is interrupted (Briki et al., 2014a)

Table 1 (*Continued*)

Variable	RM	OM	AM	BM	PM
Age	Occurs in infants (Perry et al., 2008), children (Taylor and Jakobson, 2010), adults (Hubbard, 1990), and elderly (Piotrowski and Jakobson, 2011)	Occurs in infants (McCrink and Wynn, 2009) and adults (McCrink et al., 2007)	Occurs in adults (Pratt et al., 1999)	Occurs in children (Parry-Cruwys et al., 2011), adolescents (Dube and McIlvane, 2001), and adults (Mace et al., 1990)	Occurs in adolescents (Eisler and Spink, 1998) and adults (Briki et al., 2014a)
Practice and Error Feedback	Is not eliminated by feedback (Ruppel et al., 2009)	?	?	?	Increases with previous success (Feather, 1968) and feedback (Perreault et al., 1998)
Expertise	Is larger in experts for stimuli in their field of expertise (Blättler et al., 2011)	?	?	?	Relatively more important in experts than novices (Iso-Ahola and Blanchard, 1986)
Control	Decreases when observers control target motion (Jordan and Knoblich, 2004), increases if observers have previous experience controlling the target (Jordan and Hunsinger, 2008)	?	?	?	Increases if persons believe they have control (Vallerand et al., 1988), more likely in individual sports than team sports (Iso-Ahola and Dotson, 2014)
Goal Pursuit	Increases for actions congruent with goals (Hudson et al., 2016)	?	?	Increases with progress toward a goal reinforcer (Nevin, 1992)	Increases with progress toward (Vallerand et al., 1988) or increased importance of the goal or task (Markman and Guenther, 2007)
Psychopathology	Increases with schizophrenia (Jarrett et al., 2002) and decreases with mental retardation (Conners et al., 1998), is influenced by spatial neglect (Lenggenhager et al., 2012)	?	?	Effective in treatment of developmental disorders and problem behaviors (Hubbard, 2015a)	?

NOTE: Only variables and findings relevant to comparisons of different momentum-like effects are listed, and these have been included only if a variable has been investigated for two or more momentum-like effects. For a full listing of each of the variables that influence each momentum-like effect, see Appendices A-E in Hubbard (2015b). Many findings have been replicated in multiple papers, but only a single reference (first, most important, or most thorough) is given in Table 1.
RM = representational momentum; OM = operational momentum; AM = attentional momentum; BM = behavioral momentum; PM = psychological momentum; ? = there are no reported data that address this issue.

any alternative reinforcement in that environment has not been reported, but it can be hypothesized that noncontingent or alternative reinforcement might have effects on psychological momentum similar to the effects of noncontingent or alternative reinforcement on behavioral momentum.

3.3.3. Chance or guessing

If chance or guessing were responsible for the behaviors or responses attributed to momentum-like effects, then the content of those behaviors or responses would be randomly distributed around the content of the actual outcome rather than biased in a consistent direction away from the content of the actual outcome. In representational momentum, displacement is in the direction of anticipated motion. Similarly, in operational momentum, displacement is in the direction along the number line of the arithmetic operation (leftward for subtraction, rightward for addition). Behavioral momentum and psychological momentum involve a continuation of the same type of behavior. In all these cases, the content of the potential outcome is not randomly distributed around the content of the actual outcome, but is shifted in a specific direction consistent with a continuation of the action, behavior, or process; thus, a momentum-like effect reflects a consistent bias rather than reflecting random chance. Also, if participants in studies of representational momentum (involving discrete implied motion) are instructed to guess the next location where the target will be presented, they often underestimate rather than overestimate the distance to that location (Finke and Shyi, 1988; Munger and Minchew, 2002). That is, when participants explicitly guess, their pattern of guessing is different from the response pattern typically attributed to representational momentum, and this suggests that momentum-like effects do not reflect explicit guessing.

3.3.4. Sensory processing

There have been attempts to link representational momentum with sensory processes such as pursuit eye movements and visual persistence (e.g., Kerzel, 2000; Stork and Müsseler, 2004), but any success of these attempts has been limited to specific types of stimuli (e.g., smooth motion with continuous visual tracking), and such sensory processes cannot account for representational momentum with other types of stimuli (e.g., implied motion or frozen-action stimuli, see discussion in Hubbard, 2005, 2006b, 2010). It is not clear how sensory processing might account for operational momentum, although it is possible that constraints regarding movement of attention in sensory processing might contribute to attentional momentum. Behavioral momentum and psychological momentum occur over time-scales far longer than the time-scales of sensory processing, and also involve nonsensory information (e.g., preference for a given type of reinforcer, relative importance of a specific goal), and so it is unlikely that these longer time-scale types of momentum-like effects reflect sensory processing. It is possible that top-down influences on sensory processing can influence perceptual time-scale momentum-like effects (e.g., properties of functional architecture, Hubbard, 1995b, 2005, 2006a,b; effects of object identity, Reed and Vinson, 1996; Vinson and Reed, 2002), and if so, then the resultant momentum-like effects would not solely reflect sensory processing, but would reflect stimulus-specific learning as well as more general learning and expectations.

3.3.5. Practice or error feedback

Although consistent with the data available at the time, Freyd's (1987) suggestion that representational momentum is impervious to effects of practice or error feedback is less consistent with subsequent findings. The probability of a *same* response in judgments of whether a subsequently presented probe is at the same location as the final target location or at a different location is influenced by error feedback (Ruppel et al., 2009) and by the prior probability that a *same* response would be correct (Hubbard and Lange, 2010); even so, such manipulations do not influence the magnitude of representational momentum per se (i.e., such manipulations influence the height but not the skew of a distribution of *same* responses). However, larger representational momentum for stimuli in a domain of expertise (e.g., piloting aircraft, Blättler et al., 2011; driving automobiles, Blättler et al., 2010; hitting a baseball, Nakamoto et al., 2015) presumably reflects effects of practice and error feedback during skill acquisition. A claim of imperviousness of behavioral momentum and psychological momentum to effects of practice or error feedback is not tenable, as each of these latter effects is clearly dependent upon and influenced by learning. Also, manipulations (involving feedback) that influence perceived psychological momentum do not necessarily influence performance (Kerick et al., 2000), and explicit instruction involving representational momentum decreases but does not eliminate forward displacement in judgments of target location (Courtney and Hubbard, 2008).

3.3.6. Memory for position

Freyd (1987) suggested the momentum effect involved a shift in memory for position, but such a description is appropriate only for representational momentum (and perhaps operational momentum and attentional momentum, which along with representational momentum, seem to primarily reflect shifts across [some type of] space, see Hubbard, 2014). A broader view is required if representational momentum is compared with momentum-like effects more generally. Behavioral momentum and psychological momentum involve a continuation of specific behaviors rather than a continuation of movement through contiguous positions. Thus, rather than involving shifts in position, momentum-like effects can be more generally considered as a continuation of the current behavior of the target (and in the special case of representational momentum for a moving target, such a continuation would imply a shift in spatial position). Reframing representational momentum as reflecting continuation of the current behavior of the target makes representational momentum more consistent with a framing of behavioral momentum or psychological momentum as reflecting continuation of the current behavior of an object, individual, or process. Such a reframing also more satisfactorily addresses representational momentum for potentially nonspatial changes (e.g., auditory pitch).

3.3.7. Velocity

Freyd (1987) suggested the momentum effect increased with target velocity, and although this is consistent with representational momentum for movement of a physical target through a spatiotemporal coordinate system (Hubbard, 1995b, 2005, 2014), a broader interpretation more consistent with other types of momentum-like effects would suggest that momentum-like effects increase with increases in the rate of change. According to such a view, a faster rate of change is associated with a larger momentum-like effect. Rate of change in a spatiotemporal coordinate system is equivalent to velocity, and so an increase in momentum-like effects with greater rates of change is consistent with a momentum metaphor. Analogues of velocity or rate of change have not been examined for operational momentum or attentional momentum; it is not clear how such velocity might be manipulated, although presumably effects of velocity of movement of attention along the number line or across space would parallel effects in representational momentum. Psychological momentum (Mace et al., 1992; Roane et al., 2004) has been reported to increase with increases in response rate or reinforcement rate. If the analogue of velocity in behavioral momentum is response rate (e.g., Nevin, 1992; Nevin et al., 1983; Nevin and Grace, 2000), then it could be predicted that behavioral momentum should increase as response rate increases. However, reinforcement schedules producing greater response rates (while controlling reinforcement rates) result in less persistent behavior (e.g., Lattal, 1989; Nevin et al., 2001).[2]

3.3.8. Rapid occurrence

Freyd (1987) highlighted that representational momentum occurs very rapidly; however, a rapid occurrence is not necessarily characteristic of all momentum-like effects. Rapid occurrence seems to be a property of perceptual time-scale momentum-like effects (representational momentum, Freyd and Johnson, 1987; and attentional momentum, Samuel and Kat, 2003; appear to last only for a few hundred milliseconds), but longer time-scale momentum-like effects such as behavioral momentum and psychological momentum do not exhibit such a rapid rise or fall. Although the rapid rise and fall of representational momentum and attentional momentum appears relatively inflexible, the rise of behavioral momentum appears more flexible (e.g., Podlesnik and Bai, 2015); behavioral momentum appears to accrue more rapidly following prior compliance with tasks with a higher probability of compliance (Kelly and Holloway, 2015; Mace et al., 1988), with higher quality reinforcers (Mace et al., 1997), and with a higher rate of reinforcement in a multiple schedule when schedules do not alternate frequently (Craig et al., 2015). Similar patterns might be predicted for psychological momentum. Indeed, if different momentum-like effects involve a more general mechanism that operates over multiple time-scales, then momentum-like effects would not be limited to short (perceptual) time-scales, but should approximate the time-scales of the action, behavior, or outcome being extrapolated. Thus, rapid occurrence is not necessarily a property of momentum-like effects in general.

3.3.9. Retention interval

Related to the idea that momentum-like effects occur rapidly is Freyd's (1987) suggestion that momentum-like effects exhibit an increase over short retention intervals. Numerous studies of representational momentum found that forward displacement increases with increases in retention interval up to 250–300 milliseconds and then declines (reviewed in Hubbard, 2005). Similarly, attentional momentum is present at ISIs of 600 milliseconds but not at ISIs of 1200 milliseconds (Samuel and Kat, 2003). Behavioral momentum and psychological momentum presumably require a minimum number of trials or stimuli to develop before reaching a plateau. Although the absolute time-scales of different momentum-like effects clearly differ, most forms of momentum-like effect appear to involve an initial increase of momentum that then plateaus (with a constant level of continued reinforcement) or gradually decreases. Although retention intervals in the millisecond range might be appropriate for perceptual time-scale momentum-like effects, the longer time-scale momentum-like effects such as behavioral momentum and psychological momentum exhibit retention intervals of minutes, hours, days, or longer. The idea of an initial increase in the magnitude of the momentum-like effect is consistent with momentum-like effects in general, but the idea that such an increase must occur over a short interval (of a few hundred milliseconds rather than over multiple trials of hours or days) applies only to perceptual time-scale momentum-like effects.

The notion of retention interval isn't quite clear in behavioral momentum. A parallel with representational momentum suggests that retention interval begins when reinforcement for the target behavior is discontinued. Behavioral momentum would presumably decrease until the target behavior no longer occurred (e.g., until extinction). However, behavioral momentum theory, unlike representational momentum theory, includes a mechanism for momentum effects to subsequently re-occur (Nevin and Shahan, 2011). This reoccurrence is generally referred to as *relapse*, and more specifically referred to as *resurgence* if reoccurrence follows discontinuation of alternative reinforcement and *reinstatement* if reoccurrence follows reintroduction of reinforcement (e.g., Nevin et al., 2016). Relapse has been extensively studied within behavioral momentum literature (e.g., Bai et al., 2016; Craig and Shahan, 2016; Podlesnik and Fleet, 2014; Podlesnik and Shahan, 2009, 2010; Shahan and Sweeney, 2011), but parallels to relapse for other forms of momentum-like effect are not clear. One possibility is that relapse might reflect a residual of motor learning that is absent from momentum-like effects that occur at the perceptual time-scale. A related possibility is that relapse might reflect the difference between an (animate) actor or agent generating the target behavior and an (inanimate) external stimulus exhibiting the target behavior. Alternatively, apparent extinction (or other disruption to responding) might reflect a temporal interference or interruption of responding rather than a full decay of behavioral momentum.

3.3.10. Attachment to an object

Freyd (1987) suggested representational momentum is attached to a specific object rather than to a context or to a general or abstract frame of reference. This is consistent with findings of decreased or no representational momentum for a target that did not maintain a consistent identity (Kelly and Freyd, 1987) and with findings that the identity of a target (Reed and Vinson, 1996) and whether the source of target motion is attributed to the target or to a force external to the target (Hubbard et al., 2001; Hubbard, 2013) influence representational momentum. The view that momentum is attached to a specific object and not to a context or an abstract frame of reference is consistent with Cooper and Shepard's (1973) notion that mental rotation must involve a specific object and not an abstract frame of reference, and this is consistent with Munger, Solberg, and Horrocks's (1999) suggestion of similarities of representational momentum and mental rotation (see also Hubbard, 2006a). Behavioral momentum appears similarly attached to a specific behavior within a given context, and psychological momentum appears attached to a specific outcome within a given context. However, attachment to a specific target does not mean representational momentum is limited to a single stimulus, as direction-appropriate representational momentum is observed for each stimulus in a multiple stimulus display (Finke and Freyd, 1985) or scene (Thornton and Hayes, 2004); this is consistent with the possibility of momentum-like effects for multiple behaviors within a multiple-schedules methodology or for multiple individuals on a team.

3.3.11. Non-Rigid visual transformation

Early studies of representational momentum typically presented geometric or other visual stimuli undergoing rigid change

[2] There are several possible ways to reconcile this finding with the notion that increases in the analogue of velocity increase a momentum-like effect. The first possibility is that requiring a greater response rate for the same amount of reinforcement actually decreases the behavioral mass (i.e., the target becomes less important or less desirable, cf. Markman & Guenther's, 2007, notion that the magnitude of psychological mass is related to the importance of the goal), and that this decrease in behavioral mass is larger than any increase due to increases in response rate (i.e., velocity). A second possibility is that increases in response rate if reinforcement is held constant result in a smaller amount of reinforcement per response. It might be that the level of persistence reflects the amount of reinforcement per response rather than the absolute response rate. Such a concern would obviously not arise for representational momentum, operational momentum, or attentional momentum, although the extent to which such a concern would arise for psychological momentum is unknown. A third possibility is that additional required effort is analogous to increases in friction or resistance; this would be consistent with findings that increases in implied friction on a visual moving target can decrease effects of velocity on representational momentum (Hubbard, 1995a). Resolution of this awaits future studies.

(e.g., translation, rotation, etc.), but Freyd (1987) suggested representational momentum might be found for other dimensions of change. Indeed, representational momentum has subsequently been found for (nonrigid) deformation of visual shape (Kelly and Freyd, 1987) and changes in auditory (Getzmann et al., 2004; Johnston and Jones, 2006) and tactile (Brouwer et al., 2005) stimuli. It is not clear what a nonrigid transformation involving operational momentum (although a logarithmically scaled representation of quantity that compressed larger magnitudes might be considered more nonrigid than a linearly scaled representation of quantity) or involving attentional momentum would entail. Given the wide range of behaviors that can exhibit behavioral momentum or psychological momentum (e.g., see Hubbard, 2015a; Iso-Ahola and Dotson, 2014; Nevin, 2015), it seems implausible to limit behavioral momentum or psychological momentum to any type of artificially rigid behavior, performance, or process. More broadly, momentum-like effects can occur for any type of action, behavior, or outcome in which a continuation of that action, behavior, or outcome can be extrapolated into the near future (cf. Finke et al., 1986; Hubbard, 2014). This broader view allows momentum-like effects to occur in stimulus dimensions which might not experience effects of physical momentum but which exhibit continuous change (e.g., auditory pitch).

4. Constraints and consequences for a future theory

It is possible that multiple mechanisms for producing momentum-like effects exist, each of which produces a momentum-like effect for a different stimulus dimension, modality, or time-scale. Alternatively, and given the similarities of different momentum-like effects discussed in Section 3, it is possible that a smaller number or even a single more general mechanism might operate over a range of different dimensions and modalities (Hubbard, 2005, 2006a,b) or time-scales (cf. Hubbard, 2015b; Jordan, 2013). The properties discussed in Section 3.3, in conjunction with data regarding the variables listed in Table 1 and reviewed in Hubbard (2014, 2015a,b), suggest such a general mechanism would have a number of constraints and consequences that would need to be addressed by any future theory of momentum-like effects. These include dynamic representation, the nature of extrapolation, sensitivity to environmental contingencies, bridging gaps between stimulus and response, increasing adaptiveness of the organism to the environment, serving as a heuristic for perception and action, insensitivity to stimulus format, importance of subjective rather than objective consequences, role of knowledge and belief, automaticity of occurrence, and properties of the functional architecture.

4.1. Dynamic representation

Freyd (1987) suggested that representational momentum reflected dynamic aspects of representation, and it is possible that other momentum-like effects also reflect dynamic representation. There are at least two senses of “dynamic” that are relevant. The first sense of “dynamic” is a colloquial sense involving movement or change over time. Related to this is the importance of temporal information in representation (e.g., temporal information is necessary to distinguish between cause and effect or between stimulus and response) and the idea that time is an intrinsic and necessary aspect of representation (cf. Freyd, 1987). Furthermore, momentum-like effects change over time; such changes typically involve an initial increase and/or a subsequent decrease, and the subsequent decrease might occur quickly (e.g., representational momentum for a moving target) or slowly (e.g., extinction of a well-learned behavior). Representational momentum rapidly increases and then decreases (for review, Hubbard, 2005), and a similar increase and subsequent decrease with increases in temporal interval between reinforcers occurs with behavioral momentum (Craig et al., 2015) and psychological momentum (Iso-Ahola and Dotson, 2014). Although representational momentum, operational momentum, and attentional momentum involve extrapolation through (some type of) space, momentum-like effects involving movement in space also unfold in time, and behavioral momentum and psychological momentum also involve extrapolation through time.

A second sense of “dynamic” is a technical sense in physics and refers to the presence of force. Dynamics differs from kinematics or geometry, which do not consider force. Shepard (1984, 1994) argued for internalization of kinematic and geometric information but not dynamic information, but evidence from momentum-like effects suggests that at least some dynamic information might also be internalized; indeed, information regarding momentum, as well as information regarding other forces such as gravity and friction, influence displacement in localization of a target (for review, Hubbard, 1995b, 2005). Interestingly, Shepard’s (1975, 1981) notion of a second-order isomorphism, which was originally proposed to account for observations that visual imagery appears to preserve kinematic and geometric information, also predicts the presence of dynamic information such as representational momentum: A distal object rotating from orientation A to orientation C must pass through an intermediate orientation B, and Shepard suggested the mental representation of an object rotating from orientation A to orientation C must also pass though an intermediate orientation B. A distal object rotating from orientation A to orientation C would also possess momentum, and Hubbard (2006a) suggested the mental representation of an object rotating from orientation A to orientation C must also possess (an analogue of) momentum, that is, representational momentum. Thus, momentum-like effects reflect dynamic properties of representation in both colloquial and technical senses of “dynamic” (see Hubbard, 2014, 2015a,b).

4.2. Extrapolation

All forms of momentum-like effect involve some type of extrapolation of a current action, behavior, or outcome to a future action, behavior, or outcome. This typically involves persistence of the current action or behavior of the stimulus or the observer, although this can be influenced by expectations regarding upcoming stimulus behavior (e.g., regarding a change in the direction of motion). Extrapolation involves both spatial information and temporal information; even so, momentum-like effects that occur on perceptual time-scales appear to emphasize extrapolation through space (Hubbard, 2014), whereas momentum-like effects that occur on longer time-scales appear to emphasize extrapolation through time (Hubbard, 2015a). However, there are at least two senses of “extrapolation” that are relevant. The first sense of “extrapolation” involves a change (e.g., of location, in which a linearly moving target is displaced further in the direction of movement), whereas the second sense of “extrapolation” involves a nonchanging continuation (e.g., a specific behavior continues unchanged in the absence of reinforcement).[3] The property of continuation discussed earlier

[3] Interestingly, the difference between extrapolation involving change and extrapolation involving continuation is somewhat reminiscent of the difference between metathetic stimuli and prothetic stimuli in psychophysics (see Stevens, 1975). Metathetic stimuli involve those in which a change in intensity changes the fundamental nature of the experience (e.g., an increase in wavelength changes the hue experienced rather than the intensity of a hue, e.g., red is not “more” or “less” than green), whereas prothetic stimuli involve those in which a change in intensity does not change the fundamental nature of the experience (e.g., an increase in

includes both of these senses, but it is not yet clear whether the difference between change and continuation will be a meaningful one in any future theory of momentum-like effects. Interestingly, most examples of perceptual time-scale momentum-like effects involve change (e.g., of orientation), whereas most examples of longer time-scale momentum-like effects involve continuation (e.g., of a specific behavior).

4.3. Environmental contingencies

All momentum-like effects are influenced by environmental contingencies. In some momentum-like effects, these contingencies reflect invariant aspects of the environment (e.g., physical principles governing motion) that have been incorporated into functional properties of the cognitive architecture (e.g., Hubbard, 1995b, 1999, 2005, 2006a,b). Such incorporation is reminiscent of Gibson's (1966, 1979) notion of invariants that are picked up by a perceiver, and so such an incorporation of environmentally invariant information into perceptual or cognitive representation offers a potential bridge connecting ecological approaches and representational approaches by positing that invariant information shaped the functional architecture of the representational system. In other momentum-like effects, these contingencies reflect beliefs based on stochastic or arbitrary aspects of the environment that have been learned. This is demonstrated in the role of reinforcement in behavioral momentum (e.g., Mace et al., 2010; Nevin and Grace, 2000; Podlesnik et al., 2012a; Podlesnik et al., 2012b) and psychological momentum (e.g., Mace et al., 1992; Markman and Guenther, 2007). In general, environmental contingencies involving invariant information (e.g., effects of momentum, gravity, friction), and environmental contingencies involving variable, arbitrary, or idiosyncratic information (e.g., word meanings, color associated with food pellet delivery), influence momentum-like effects.

4.4. Bridging or filling a gap

Sensitivity to environmental contingencies can help an observer bridge or fill the gap between a stimulus and a response. In representational momentum, the gap is generally between perception and action, and the momentum-like effect helps observers more efficiently interact with moving objects in real time. In behavioral momentum or in psychological momentum, the gap is between behavior and subsequent reinforcement, and bridging this gap becomes particularly important if delivery of reinforcement is intermittent (e.g., on a partial schedule) or delayed. The gap can be short (e.g., hundreds of milliseconds for representational momentum) or long (minutes, hours, days, or more for behavioral momentum and psychological momentum). The gap-filling property of momentum-like effects is similar to the ideas of Pragnanz and the Gestalt principles of perceptual grouping involving closure and good continuation, in that momentum-like effects aid completion of an incomplete stimulus (e.g., a partially or intermittently occluded target, a perception [behavior] and action [reinforcement] pairing) and bias perception and behavior toward the most likely stimulus action or most optimal response, respectively (see Hubbard, 2011). Relatedly, in operational momentum or in attentional momentum, the momentum-like effect results from movement of attention (across numeric space or physical space, respectively), and this movement bridges or fills the gap between the initially cued location and a subsequent (goal) location.

4.5. Adaptiveness

Sensitivity to environmental contingences and an ability to bridge or fill the gap between stimulus and response can increase the adaptiveness of an organism to the environment. For example, representational momentum might aid in compensating for neural processing times in interactions with moving targets. Without such an adaptation, perception of the position of a moving target would lag behind the actual position of that target, because the target would continue to move after the sensation was initiated but before that sensation reached perceptual awareness (see Fig. 6 and discussion in Hubbard, 2005; also Nijhawan, 2008). By displacing the represented position slightly forward, the representation specifies where the target would be at that moment in real-time rather than where the target was when sensation began. As noted in Hubbard (2014), it is not clear that operational momentum and attentional momentum are similarly adaptive, but these latter two effects might reflect generalizations of representational momentum that were not harmful enough to be selected against. Behavioral momentum and psychological momentum can be viewed as adaptive if such effects facilitate recognition of or responding to subsequent stimuli in the absence of reinforcement and as decreasing the likelihood of extinction of learned behaviors during a temporary absence of external reinforcement (e.g., with a partial reinforcement schedule or if reinforcement is delayed or inhibited).

The adaptiveness of momentum-like effects is related to the potential evolutionary origins of such effects. Aside from one study possibly demonstrating representational momentum in pigeons (Neiworth and Rilling, 1987), the only momentum-like effect studied in nonhuman populations has been behavioral momentum. Given that representational momentum can aid in compensating for delays in perception due to neural processing times and allow interactions with moving objects in real time, such an effect would clearly be advantageous for nonhuman animals (e.g., a predator attacking fleeing prey) as well as for humans. It is possible that mechanisms responsible for momentum-like effects in one dimension, modality, or time-scale were appropriated for production of momentum-like effects in other dimensions, modalities, or time-scales; this would be consistent with examples in which structures initially evolved for one purpose could subsequently be used for a different purpose (e.g., Clark, 1987; Marcus, 2008). Consistent with this, existence of a single or small number of mechanisms has previously been suggested on the basis of parsimony (e.g., Hubbard, 2006b, 2014, 2015b), but there is no reason to assume evolutionary processes necessarily arrived at a parsimonious solution (e.g., it is possible that different mechanisms evolved for momentum-like effects at different time-scales, and this would be consistent with speculation regarding development of action control at multiple time-scales, cf. Jordan, 2008).[4]

4.6. A momentum heuristic

Momentum-like effects could serve as heuristics to facilitate perception and action for the most likely actions, behaviors, or

amplitude changes the loudness of a pitch, e.g., a loud F# is "more" than a soft F#, but the pitch is still a F#). More specifically, extrapolation involving change is more metathetic, and extrapolation involving continuation is more prothetic. Whether this difference might be important for theories of momentum-like effects is not yet known.

[4] Even if different momentum-like effects result from different physiological mechanisms, such differences might simply reflect differences in algorithms or neural instantiation and not differences in the underlying computational theory (for general discussion of these levels, see Marr, 1982; for discussion of these levels applied to representational momentum, see Hubbard, 2005). In general, all forms of momentum-like effect can be viewed as helping the organism solve the problem of predicting upcoming actions, behaviors, and outcomes, and so the different forms of momentum-like effect are unified at the level of computational theory.

outcomes that would be encountered. As with all heuristics, momentum-like effects do not necessarily lead to physically or statistically correct outcomes, but do lead to outcomes that are sufficient for most predictive purposes. For example, some cases of representational momentum appear to be based on a naïve physics notion of impetus rather than on a correct understanding of momentum (e.g., Hubbard et al., 2001; Kozhevnikov and Hegarty, 2001). Although impetus is not a valid physical principle, predictions based on an impetus notion can nonetheless yield a prediction that is "good enough" for most purposes (e.g., a target that is pushed will move a short distance and then stop) but takes less effort and fewer cognitive resources than would a prediction based on multiple physical qualities such as mass, inertia, resistance, etc. Although mechanisms that produce momentum-like effects can result in systematic errors (e.g., Einstellung effect, hot hand effect, etc.), the usefulness of momentum-like effects in the majority of situations that would be encountered presumably outweighs any occasional errors that can arise. According to such a view, momentum-like effects are not an error, but are a heuristic that evolved to bias perception and action in ways likely to be consistent with subsequent experience, and thus maximize useful prediction of actions, behaviors, and outcomes with minimal cost (Hubbard, 2004, 2005, 2006a, 2014).

4.7. Format

If momentum-like effects are to be maximally adaptive or useful as a heuristic, then they should be sensitive to the information (i.e., meaning) suggested by a given stimulus and not dependent on the format (i.e., surface features) of that stimulus. As noted earlier, representational momentum is found with continuous motion, implied motion, and frozen-action stimuli, and operational momentum is found with symbolic numerals, dot clusters, and pointing to a location along a line. Behavioral momentum is found in a wide range of behaviors in laboratory, clinical, or everyday settings, and psychological momentum occurs for a wide range of competitive or noncompetitive tasks. Interestingly, the relative insensitivity to stimulus format is consistent with findings on understanding text, in which memory usually corresponds to the meaning (gist) and not to the specific phrasing (e.g., Bransford et al., 1972; Bransford and Franks, 1971; Sachs, 1967). Also, occurrence of momentum-like effects with a variety of stimulus formats suggests that such effects are not purely perceptual or low-level but also involve high-level processes. As noted earlier, a criterion of parsimony cannot be unequivocally applied to evolutionary processes; even so, it is more parsimonious to posit a smaller number of mechanisms (or even a single mechanism) that operate(s) at a high level of processing and result(s) in momentum-like effects for different types of stimuli (cf. Hubbard, 2005, 2006a,b) and over different time scales (cf. Hubbard, 2015b; Jordan, 2013) than to posit a larger number of mechanisms that result in momentum-like effects for different stimulus dimensions, modalities, and time-scales.

4.8. Subjective consequences

Sensitivity to environmental contingencies does not imply or require sensitivity to the details of objective physical principles per se, but only requires sensitivity to information regarding the effects of those principles for the individual. Consistent with this, momentum-like effects appear to reflect subjective consequences of environmental contingences rather than physically or statistically objective consequences of environmental contingences. In representational momentum, effects of mass are experienced in the direction of gravitational attraction and not in the direction of motion and appear to be subjectively experienced as effects of weight (Hubbard, 1997, 2006a). Psychological mass of a behavior or outcome has been suggested to relate to the subjective importance or value of that behavior or outcome (Markman and Guenther, 2007). As suggested by Hubbard (2015b), perhaps "psychological weight" and "behavioral weight" would be more appropriate (and more consistent with colloquial language in which issues of greater importance are said to have more weight) than "psychological mass" and "behavioral mass". Displacement in numeric space appears to be influenced by a subjective compression of larger magnitudes and not by the objective (linear) distances between magnitudes. The effect of valence in psychological momentum is related to the subjective consequences of success or failure, which often appear more salient or vivid than the objective consequences of success or failure.

4.9. Knowledge and beliefs

The knowledge or belief of an observer regarding an action, behavior, or outcome can in some cases cognitively penetrate (i.e., influence) momentum-like effects for that action, behavior, or outcome. This knowledge or belief can involve variant or invariant information or involve implicit or explicit information; however, it is not yet clear what determines whether a momentum-like effect will be cognitively penetrable or cognitively impenetrable to a specific exemplar of knowledge or belief.

4.9.1. Variable or invariant experience

Beliefs often involve perceived environmental contingencies, and as noted earlier, momentum-like effects are sensitive to expectations derived from experience or beliefs regarding such contingencies. If experience is invariant (e.g., effects of momentum on physical objects), then behavioral or cognitive effects based on those contingencies are more likely to be consistent with physical and statistical laws. However, if experience is variable or if recent experience would constitute an outlier, then behavioral or cognitive effects based on those contingencies are more likely to be inconsistent with physical and statistical laws (e.g., the hot hand effect); extrapolation of a momentum-like effect in such circumstances would suggest an atypical level of performance would continue, even though performance should be expected to statistically regress. To be maximally efficient (e.g., not require additional attentional resources), information regarding invariants should be incorporated into the functional architecture of representation. As a consequence, the stronger the invariance, the less likely other information (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 explicit knowledge; Finke and Freyd, 1989; Hubbard, 2005, 2006a]). In cases where there is no obvious relevant physical invariant (e.g., psychological momentum in sport competition), the momentum-like effect might be driven entirely by belief.

4.9.2. Implicit or explicit knowledge

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 greater 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 and Jones, 1994; Kozhevnikov and Hegarty, 2001). Thus, any theory of momentum-like effects should specify when explicit information would influence momentum-like effects and when explicit information would not influence momentum-like effects. One possibility is that explicit knowledge influences momentum-like effects as a function of its relevance, but this possibility can be rejected, as highly relevant knowledge can influence (e.g., object identity, Reed and Vinson, 1996) or not influence (e.g., Newtonian physics, Freyd and Jones, 1994; Kozhevnikov and 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 aspects rather than invariant aspects of the target, behavior, or process (as invariant information might be more likely to be incorporated into the functional architecture). However, whether a distinction between implicit and explicit knowledge would be meaningful in studies of momentum-like effects in nonhuman animals is not clear. Ultimately, a momentum-like effect might reflect implicit information, explicit information, or a combination of implicit information and explicit information.[5]

4.9.3. Cognitively penetrable or impenetrable

Related to the potential role of belief within momentum-like effects is the potential cognitive penetrability of momentum-like effects. Momentum-like effects might involve both cognitively penetrable components (influenced by beliefs, knowledge, and expectations) and cognitively impenetrable components (not influenced by beliefs, knowledge, and expectations), and this is consistent with findings that representational momentum can be decreased (by influencing cognitively penetrable components) but not eliminated (because of the presence of cognitively impenetrable components) by explicit instruction (Courtney and Hubbard, 2008) or by cueing final target location (Hubbard et al., 2009). Some types of information influence momentum-like effects (e.g., knowledge of probable target direction, Johnston and Jones, 2006; Verfaillie and d'Ydewalle, 1991; feedback about one's performance, Kerick et al., 2000), whereas other types of information do not influence momentum-like effects (e.g., prior probabilities, Gilovich et al., 1985; Hubbard and Lange, 2010). Verbal semantic knowledge can influence momentum-like effects (e.g., a verbal cue describing target motion, Hubbard, 1994; a verbal label identifying the semantic category of the target, Reed and Vinson, 1996). Beliefs regarding importance or value of a behavior or outcome modulate psychological mass of that behavior or outcome, and thus influence psychological momentum (Markman and Guenther, 2007). However, whether a distinction between cognitively penetrable information and cognitively impenetrable information would be meaningful in studies of momentum-like effects in nonhuman animals is not clear.

4.10. Automaticity

Momentum-like effects occur automatically and do not result from explicit or deliberative prediction of future action, behavior, or outcome. Explicit attention during target presentation does not appear necessary for generation of most momentum-like effects, although attentional momentum might be an exception. Consistent with this, representational momentum (Hayes and Freyd, 2002), operational momentum (McCrink & Hubbard, in press), and behavioral momentum (Podlesnik et al., 2012b) appear increased with divided attention (i.e., if potentially less attention can be allocated to the target). Similarly, the possible existence of representational momentum in laboratory animals, and the clear existence of behavioral momentum in laboratory animals, suggests that explicit or conscious verbal processing is not necessary for generation of momentum-like effects. Indeed, and as noted earlier, explicit prediction of the future location of a target results in backward or no displacement from the actual future location rather than in the forward displacement typical of representational momentum (e.g., Finke and Shyi, 1988; Munger and Minchew, 2002). Furthermore, it appears that psychological momentum experienced by spectators or participants in sporting events occurs automatically, although evidence for this is only anecdotal. Given the heuristic nature of momentum-like effects, such effects would be most effective if they were automatically evoked and did not require allocation of attentional or cognitive resources.

4.11. Functional architecture

Different neural architectures could potentially be implicated for different types of momentum-like effects, and such architectures might function as subroutines into which information regarding the current action, behavior, or outcome might be entered. Such a system would not be fully modular (in the Fodorian sense of being informationally encapsulated), as other information possessed by an individual (e.g., general or specific information regarding the action, behavior, or process) could potentially influence output of the extrapolation mechanism (e.g., if a change in direction is expected, representational momentum is reduced or reversed; if a goal is highly valued, reaching that goal results in greater psychological momentum than reaching a similarly difficult but less meaningful or less important goal). Such a subroutine would need to function rapidly and automatically. This might be most easily accomplished by incorporating such mechanisms into the functional architecture of the representational system, rather than having such functions separately computed and then applied to a representation. In other words, the efficiency of momentum-like effects could be enhanced if such effects were hard-wired into the representational system but could be modulated by stimulus-specific information (see Hubbard, 2006a). Such an incorporation could have been selected for over the course of evolution, and as a consequence, perception would be modulated by the potential effects of action (cf. Hommel et al., 2001; Philbeck and Witt, 2015).

5. Summary and conclusions

The future actions, behaviors, and outcomes of objects, individuals, and processes can often be anticipated, and some of these anticipations have been hypothesized to result from momentum-like processes. Five types of momentum-like effect have been discussed in the literature, and these include representational momentum, operational momentum, attentional momentum, behavioral momentum, and psychological momentum. The first three operate on a perceptual time-scale (milliseconds), and the last two operate on a longer time-scale (minutes, hours, days, or longer). Similarities in the properties of different types of momentum-like effects, and potential constraints on and consequences for any future general theory of momentum-like effects, were considered. These considerations built on previous findings that specific variables influence different momentum-like effects in similar ways (Hubbard, 2014, 2015a,b) and suggest that different forms of momentum-like effect might involve similar mechanisms or even the same more general mechanism. If these different forms

[5] Hubbard (2006a; see also Courtney and Hubbard, 2008) proposed that displacement observed in studies of representational momentum resulted from two separate factors involving (a) a second-order isomorphism between subjective consequences of physical principles on physical objects and the mental representations of those objects that provided an automatic default displacement and (b) physical or cognitive context (including beliefs) that could modulate this default displacement. The first factor reflects a property of the functional architecture of the representation, and the second factor reflects other information about the target (including beliefs) that could modulate the output of the first factor. To the extent that operational momentum and attentional momentum are special cases of representational momentum, these two effects could be predicted to result (at least in part) from an automatic extrapolation that could be modulated but not eliminated by an observer's beliefs (although whether beliefs might influence operational momentum or attentional momentum has not been investigated). Whether behavioral momentum and psychological momentum result from a similar process in which at least one factor represents an internalization of momentum and at least one factor represents contextual information (such as provided by beliefs) that can modulate the momentum-like effect is not clear, and it is possible that behavioral momentum and psychological momentum might result solely from the second type of factor.

of momentum-like effect reflect a general extrapolation mechanism that operates on different stimulus dimensions, modalities, and time-scales, then a broad range of findings from areas as diverse as perception, learning theory, behavior analysis, and sport psychology could be accounted for with the same set of processes and principles.

If different momentum-like effects reflect a general extrapolation mechanism, then different momentum-like effects should exhibit similar properties. Several properties of representational momentum suggested by Freyd (1987) are consistent with properties of other momentum-like effects, and these include continuation, coherence, not resulting from chance or guessing, not resulting from sensory processes, being attached to a specific object (or objects) rather than to an abstract frame of reference, and occurring for dimensions of change other than rigid visual transformation. However, other properties proposed by Freyd (1987) are not completely consistent with properties of other momentum-like effects. The property that momentum-like effects are impervious to practice or error feedback would clearly not apply to behavioral momentum or psychological momentum, and was shown by subsequent research to not apply to representational momentum. The property that momentum-like effects result in a shift in position is too narrow, but if reinterpreted more broadly as a continuation of current behavior, is consistent with other momentum-like effects. Similarly, the property of increasing with velocity is too narrow, but if reinterpreted as increases with increases in the rate of change, is consistent with other momentum-like effects. Properties involving a rapid occurrence and an increase over short retention intervals are also too narrow, but if viewed as a general temporal profile involving an initial increase and then a steady-state or decline, are more consistent with other momentum-like effects.

Consideration of the similarities of different momentum-like effects suggests several constraints for any future theory of momentum-like effects. Momentum-like effects involve dynamic aspects of representation, as such effects involve movement and change over time as well as incorporate information about invariant environmental forces. Momentum-like effects involve extrapolation of subsequent behavior, but sometimes extrapolation involves a simple continuation of the current behavior, and other times extrapolation involves a continuation of a consistent direction or type of change in behavior. Momentum-like effects are sensitive to a range of environmental contingences. Momentum-like effects are useful in bridging between stimulus and response (e.g., between perception and action or between action and reinforcement), and this increases the adaptiveness of the organism to the environment, as the organism is better able to anticipate what might be next encountered. Along these lines, momentum-like effects function as a heuristic. Like all heuristics, a momentum heuristic doesn't always yield correct answers, but requires fewer cognitive resources to generate an answer that is good enough for most predictive purposes. Momentum-like effects are relatively insensitive to the format (surface features) of a stimulus, but instead reflect the underlying information (meaning). Momentum-like effects generally specify subjective consequences of a stimulus or action to the observer and do not necessarily reflect objective principles per se.

An important issue regarding momentum-like effects is the extent to which an individual's knowledge or beliefs influence such effects, and this is also related to issues of cognitive penetrability, automaticity, and functional architecture. Experiences involving invariant information (e.g., effects of momentum on a physical object) are more likely to have been incorporated into the functional architecture than are experiences involving variable information; indeed, by incorporating effects of an invariant experience into the representation, such effects can be represented rapidly and without any additional cost in attention or other resources (i.e., automatically evoked). However, it would be useful if stimulus-specific knowledge could also be brought to bear, and so this initial momentum-like effect can in some cases be modulated by beliefs regarding the target (for such a theory involving representational momentum, see Hubbard, 2006b; for such a theory involving psychological momentum, see Iso-Ahola and Dotson, 2014, 2016). Interestingly, influences of knowledge or belief on momentum-like effects appear to be relatively greater for longer time-scale momentum-like effects than for perceptual time-scale momentum-like effects, and this is consistent with the idea that longer time-scale momentum-like effects might be more influenced by knowledge and beliefs than are perceptual time-scale momentum-like effects. Also, and in human experimental participants, it is not clear when explicit knowledge of a stimulus will or will not influence a momentum-like effect.

Momentum-like effects occur in a wide variety of domains of activity in humans and in nonhuman animals. Studies of different momentum-like effects arose out of different areas of interest within psychological science, and so the literatures of different momentum-like effects have remained relatively isolated and often involved different methodologies and nomenclature. Nonetheless, there are many similarities across different momentum-like effects, and these involve the effects of a given variable across different momentum-like effects and the properties of different momentum-like effects. These similarities suggest specific constraints for a future theory of momentum-like effects. Also, at least some potential differences between different types of momentum-like effects might reflect a lack of investigation in a specific domain rather than an actual difference between any two types of momentum-like effect. Given this, comparisons of different momentum-like effects have considerable heuristic value in generating new hypotheses and applications. The idea of a more general extrapolation mechanism that generates momentum-like effects for a variety of stimulus dimensions, modalities, and time-scales also has considerable heuristic value. Importantly, the ubiquity of momentum-like effects suggests they might provide a fundamental method of adaptation to the environment by aiding observers in anticipating what might be next encountered and calibrating their perceptions and actions to best respond to environmental stimuli.

Author notes

The author thanks two anonymous reviewers for helpful comments on a previous version of the manuscript.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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