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THEORETICAL REVIEW

Forms of momentum across space: Representational, operational, and attentional

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Abstract Cognition can exhibit biases consistent with future expectations, and some of these biases result in momentum-like effects and have been linked with the idea of an internalization of the effects of momentum. These momentum-like effects include representational momentum, operational momentum, and attentional momentum. Similarities and differences between these different momentum-like effects are considered. Hubbard's (2005) review of representational momentum is updated to include studies published since that review appeared, and the first full reviews of operational momentum and attentional momentum are provided. It is suggested that (1) many variables that influence one of these momentum-like effects have a similar influence on another momentum-like effect, (2) representational momentum, operational momentum, and attentional momentum reflect similar or overlapping mechanisms, and operational momentum and attentional momentum are special cases of representational momentum, and (3) representational momentum, operational momentum, and attentional momentum reflect properties of a more general spatial representation in which change or transformation of a stimulus is mapped onto motion in a spatial coordinate system.

Keywords Representational momentum · Operational momentum · Attentional momentum · Spatial representation · Dynamics · Displacement

The cognitive representation of a stimulus or process is often displaced forward in ways that anticipate the subsequent action of that stimulus or process (e.g., a moving target is judged to have traveled slightly farther than it actually traveled). This forward displacement has been found with different types of stimuli, and it is often described as or attributed to a momentum-like effect. Different names have been given to the forward displacements that occur in different types of stimuli, and examples include representational momentum (e.g., Freyd & Finke, 1984), operational momentum (e.g., McCrink, Dehaene, & Dehaene-Lambertz, 2007), and attentional momentum (e.g., Pratt, Spalek, & Bradshaw, 1999). One of the purposes here is to consider whether representational momentum, operational momentum, and attentional momentum are separate effects or result from similar or overlapping mechanisms. Each of these effects is reviewed, and similarities and differences amongst these effects are considered. Representational momentum has a large literature comprehensively reviewed in previous papers, and so only findings that appeared since those papers were published are reviewed here (for completeness, findings on representational momentum reviewed in previous papers are summarized in the Appendix). Operational momentum and attentional momentum have smaller literatures that are comprehensively reviewed for the first time, and these reviews are presented in the same general framework as the review of representational momentum in Hubbard (2005).

Although representational momentum, operational momentum, and attentional momentum are each reviewed in detail below, it would be helpful to begin with a brief initial description of each of these momentum-like effects. Representational momentum, operational momentum, and attentional momentum each involve an analogy with physical momentum; physical momentum is the product of velocity and mass, and it describes the behavior of matter in motion. Representational momentum involves displacement of the judged position of a moving target in the direction of anticipated motion (e.g., if a target is moving from left to right and then vanishes, observers indicate that the final position of the target is slightly to the right of the actual final position). Operational momentum involves overestimation of sums in addition and underestimation of differences in subtraction

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(i.e., the response is further along the number line in the direction of motion than is the actual sum or difference). Attentional momentum suggests that a change in the direction of movement of attention across space must first overcome momentum in the current direction of movement (e.g., more time is required to detect a target not in the current direction of movement of attention than to detect a target further along in the current direction of movement of attention). These different forms of momentum-like effect are relevant to everyday tasks (e.g., interactions with objects, impressions of quantity, shifts of attention between stimuli) and so are of considerable empirical and theoretical interest.

Theories regarding representational momentum (for a review, see Hubbard, 2010), operational momentum (e.g., Knops, Zitzmann, & McCrink, 2013), and attentional momentum (e.g., Pratt et al., 1999) have been proposed, and many of these theories suggest that displacement is based on momentum-like properties across some type of space. One conclusion reached here is that many variables have similar influences on more than one type of momentum-like effect. A second conclusion is that representational momentum, operational momentum, and attentional momentum are highly similar and involve overlapping mechanisms, with the most likely possibility being that operational momentum and attentional momentum are special cases of representational momentum. A third conclusion is that representational momentum, operational momentum, and attentional momentum are not tied to physical momentum or to movement through physical space but, instead, reflect properties of (an abstract or functional) spatial representation if the change or transformation of the stimulus can be mapped onto motion in a spatial coordinate system. Part I reviews recent research on representational momentum. Part II reviews operational momentum, and Part III reviews attentional momentum. Part IV presents comparisons between each of these momentum-like effects; proposes that representational momentum, operational momentum, and attentional momentum reflect properties of a more general type of spatial representation; and considers possible relationships of these three momentum-like effects. Part V provides some brief conclusions.

Part I: Representational momentum

In a typical experiment on representational momentum, participants view a computer-generated set of inducing stimuli that imply target motion in a consistent direction (referred to as *inducing stimuli*; see top panel of Fig. 1) or a smoothly (i.e., continuously) moving target. After the target vanishes, participants judge whether a subsequently presented probe is at the final target location (see top panel of Fig. 1) or indicate the final target location by positioning a cursor (usually by moving a mouse) or by touching the appropriate location in the display. Participants are more likely to respond *same* to probes slightly further in the direction of motion (see bottom panel of Fig. 1) or to position the cursor or touch a location slightly further in the direction of motion. This has been referred to as *representational momentum* (e.g., Freyd & Finke, 1984), and Hubbard (1995c, 2005) provided detailed reviews of variables that influence representational momentum. Since those reviews, a number of studies have been published, and many of these studies shed additional light on the effects of variables previously studied or documented effects of previously unstudied variables. The latter variables generally fit within Hubbard's (2005) framework of characteristics of the target, display, context, and observer, and so that framework is used here. The discussion here does not provide a complete review of representational momentum but includes only those studies that appeared since Hubbard's (2005) review (although earlier studies are noted when relevant, and a summary of these earlier studies is provided in the Appendix).

Target

Effects of characteristics of the target on representational momentum have been one of the most investigated areas in representational momentum literature, and several findings have recently appeared. Findings considered here involve (1) target velocity, (2) distance traveled by the target, (3) target eccentricity, (4) target mass, (5) the human face as target, (6) the human body as target, and (7) target modality.

Velocity

Hubbard (2005) noted that the increase in forward displacement with increases in target velocity was one of the most well-established effects in representational momentum literature. Getzmann and Lewald (2009) presented visual targets or auditory targets that moved with a constant velocity or with an irregular velocity. Forward displacement decreased if targets exhibited irregular velocity, and this was attributed to greater unpredictability of target motion. Actis-Grosso, Bastianelli, and Stucchi (2008) reported that forward displacement of final target position was influenced by final instantaneous velocity of the target and not influenced by target velocity earlier in the target trajectory (cf. Finke, Freyd, & Shyi, 1986). Actis-Grosso et al. suggested that this demonstrated that representational momentum was not due to a high-level mechanism (since they considered final instantaneous velocity as low-level information); however, influence of high-level event structures (e.g., predictable changes in target direction) on forward displacement also predicts effects regarding

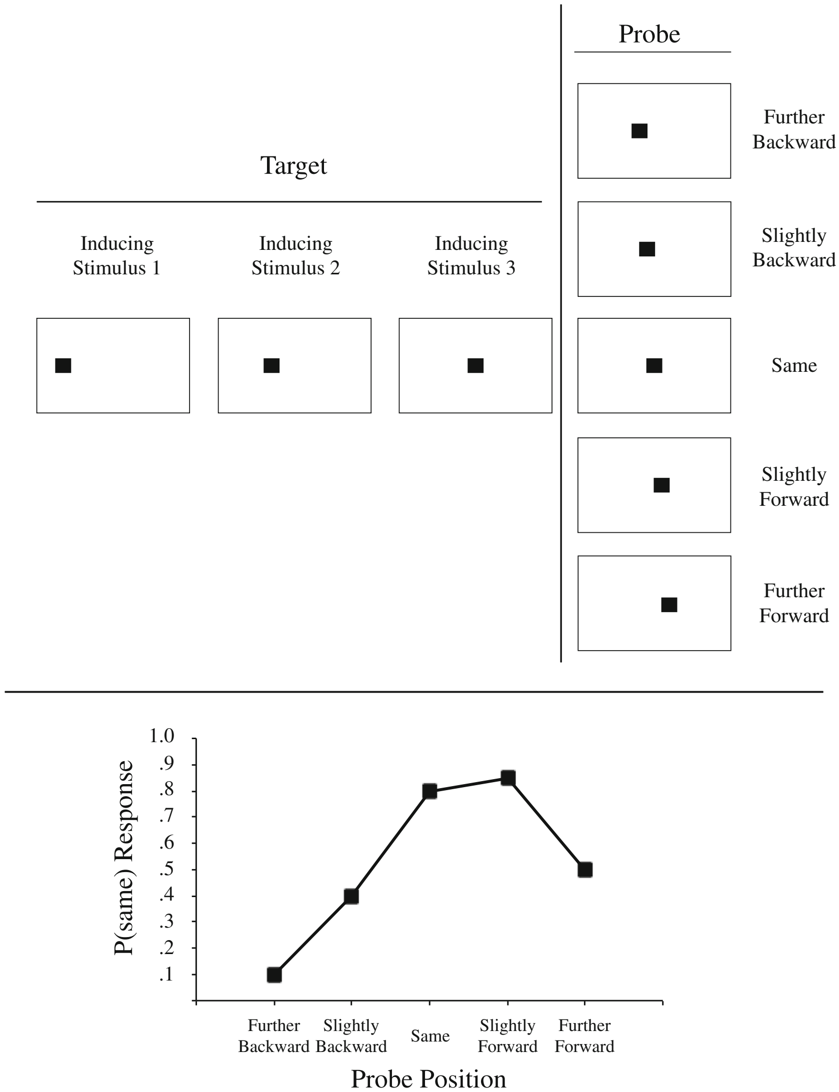

Fig. 1 An illustration of a typical methodology and results for an experiment assessing representational momentum. In the top panel, the large rectangles indicate the outlines of the display, and the small black squares indicate the target (left) or probe (right). There are three consecutive appearances of inducing stimuli that comprise the target. In this example, the target exhibits implied rightward motion (typically, each inducing stimulus is presented for 250 ms, and there is a 250-ms interstimulus interval between successive inducing stimuli and between the final inducing stimulus and probe). A probe is presented, and position of the probe relative to the actual final position of the target varies across trials (five potential probe positions are shown in the column on the right). In the bottom panel, a hypothetical but typical distribution of *same* responses as a function of probe position is illustrated. The presence of representational momentum is indicated by the higher proportion of *same* responses to probes forward of the final actual target location than to probes backward of the actual final target location

final instantaneous velocity of the target (e.g., Johnston & Jones, 2006; Verfaillie & d'Ydewalle, 1991). Schmiedchen, Freigang, Rübsamen, and Richter (2013) reported that faster velocities led to (1) larger forward displacement for visual targets moving toward or away from the midline, (2) larger forward displacement for auditory targets moving toward the midline, and (3) smaller forward displacement for auditory targets moving away from the midline. De sá Teixeira, Pimenta, and Raposo (2013) reported target velocity did not influence representational momentum in schizophrenia patients, and de sá Teixeira, Hecht, and Oliveira (2013) reported larger forward displacement with increased target velocity.

Distance

In many early studies in the representational momentum literature, the target always traveled a specific distance, and so the traveled distance was confounded with the location of the vanishing point. In other studies, vanishing point and distance traveled varied across trials, but effects of neither variable were assessed. De sá Teixeira and Oliveira (2011) attempted to disentangle effects of the distance traveled by the target and of the target vanishing point by factorially crossing distance and vanishing point for targets in trial types based on Hubbard, Blessum, and Ruppel's (2001; see also Hubbard &

Ruppel, 2002) studies of representational momentum for targets in a launching effect stimulus (see the section below on *Causality*).[1] Hubbard and Ruppel (2002) and Choi and Scholl (2006) reported that forward displacement of a launched target decreased with increasing distance traveled by that target. However, de sá Teixeira and Oliveira reported that distance traveled did not influence displacement; rather, they found an effect of vanishing point, but not of distance traveled. One possibility is that decreasing the distance of the vanishing point from the edge of the display decreases displacement (e.g., Hubbard & Motes, 2005, reported that representational momentum decreased as a target approached a boundary). Also, McGeorge, Beschin, and Della Sala (2006) found that forward displacement (1) decreased with increases in the distance traveled by a target for neglect patients and for patients with right-hemisphere damage but (2) was not influenced by the distance traveled by a target for control participants.

Eccentricity

If participants track a moving target, then presumably the target remains within the central region of the visual field, and the effects of target eccentricity cannot be measured. Given that some studies reported that forward displacement did not occur if participants did not track a smoothly moving target (de sá Teixeira, Hecht, & Oliveira, 2013; Kerzel, 2000), there was no obvious reason to examine the potential effects of target eccentricity. Nonetheless, Schmiedchen et al. (2013) examined the effects of target eccentricity on displacement of visual targets and of auditory targets that each exhibited smooth motion. Participants were instructed to look straight ahead and to not pursue the target with head or eye movements. Robust forward displacement occurred for targets that vanished in central, paracentral, and paralateral (8°, 30°, and 47° from midline, respectively) regions, and magnitude of representational momentum increased as distance from the midline increased. Schmiedchen et al. noted that this pattern was consistent with decreases in resolution acuity in paracentral and paralateral regions, since forward displacement is increased when there is greater uncertainty regarding target location (e.g., forward displacement is increased when targets are blurred; Fu, Shen, & Dan, 2001). However, the magnitude of representational momentum decreased in lateral (peripheral) regions (68° or 85° from midline), and became negative near the farthest edges of lateral space, and this was suggested to reflect a more general (and increasingly stronger) bias toward the midline (see also Schmiedchen, Freigang, Nitsche, & Rübsamen, 2012).

Mass

Previous research on representational momentum had not found a general effect of target mass on forward displacement (e.g., Hubbard, 1997), but de sá Teixeira, Oliveira, and Viegas (2008) reported that effects of size (implied mass) and effects of velocity followed an additive rule for (1) mouse pointing (i.e., cursor-positioning) and touch screen responses regarding final target location and (2) numerical estimates of how far a target would have traveled. De sá Teixeira, Oliveira, and Amorim (2010) suggested that effects of mass might interact with effects of velocity. They presented a rightward moving target that varied in size and in texture; differences in size were intended to imply differences in mass, and differences in texture (sponge, wood, metal) were intended to imply differences in density (which imply differences in mass). Participants also estimated how much effort it would take to stop the target and how long it would take the target to come to a stop. More dense targets were estimated to require more effort, but not more time, to stop. Texture, size, and velocity influenced displacement, and de sá Teixeira et al. (2010) discussed possible models for integrating size, texture, and velocity information. De sá Teixeira et al. (2010) suggested that comparison of mislocalizations with ratings revealed that mislocalizations resulted from simplification of physical principles, rather than from internalization of momentum or from isomorphism of physical properties and representational properties. Also, de sá Teixeira, Pimenta, and Raposo (2013) reported that representational momentum in schizophrenia patients increased with increases in target size.

Human face

Some of the fastest-growing areas of recent investigation within representational momentum literature involve displacement of targets consisting of (or intended to resemble) a human face or nonfacial parts of a human body. Such interest might be fueled in part by recent findings regarding embodied cognition (e.g., Barsalou, 2008; Gibbs, 2005) or mirror neurons (e.g., van der Gaag, Minderaa, & Keysers, 2007), since these findings suggest that representation of another person's face or body movements draws on an individual's knowledge regarding his or her own face or body movements. Yoshikawa and Sato (2008; see also Yoshikawa & Sato, 2006) presented participants with pictures of a neutral target face that (via software manipulation) morphed into a face exhibiting one of several different emotional expressions. Participants were presented with a probe face, and they used a slider to adjust the emotional expression of the probe face

[1] In a launching effect stimulus, an initially stationary target is visible in the display. A moving object approaches and then contacts the initially stationary target, and upon contact, the initially moving object becomes stationary and the initially stationary target moves away. If subsequent motion of the initially stationary target is attributed to contact from the initially moving object, this is referred to as a *launching effect* (for a review, see Hubbard, 2013b). Michotte (1946/1963) found that a launching effect was more likely to be reported if motion of the initially stationary target (1) began within 100 ms after contact, (2) was in the same direction as previous motion of the initially moving object, and (3) was at a velocity equal to or slower than that of the initially moving object.

to match the final emotional expression of the target face. Participants' responses reflected a more extreme expression than that of the target, and the extremity of expression increased with increases in velocity of change in facial expression of the target. Uono, Sato, and Toichi (2010) replicated these findings, and they also reported no differences in representational momentum for facial expression between participants diagnosed with pervasive developmental disorder (average age: 19 years) and age- and sex-matched control participants. Of course, there is a limited range for facial expression, and decreases in representational momentum could be predicted for movement toward more extreme expressions.

Hudson, Liu, and Jellema (2009) presented upright computer-drawn faces that rotated (around the vertical axis) toward the participant, and gaze direction of the face could lag orientation of the face, be congruent with orientation of the face, or lead orientation of the face. Control stimuli consisting of nonagentive cylinders in which gaze direction was mimicked by eyelike black and white cube shapes aligned vertically or horizontally were also presented. Two probes were presented, and participants decided which probe was most similar to the last direction (orientation) of the target stimulus. Representational momentum occurred for all stimuli. Of greater interest, representational momentum was reduced when gaze direction lagged face direction in face stimuli, whereas gaze direction did not influence representational momentum in control stimuli. One possibility is that influences of gaze direction and of face direction in face stimuli are combined (e.g., if they are in opposite directions, they partially cancel, thus reducing forward displacement), but this does not seem completely consistent with the similarity of gaze-leading and gaze-congruent conditions. Hudson et al. suggested that individuals use gaze direction of a perceived agent to anticipate that agent's intended direction of motion. Hudson and Jellema (2011) found that representational momentum for head direction increased if emotional expression was inconsistent with an approach toward the observer (i.e., fear, disgust) and gaze was directed in front of head direction.

Human body

Wilson, Lancaster, and Emmorey (2010) presented individuals fluent in sign language and a control group with no experience in sign language with stimuli consisting of gestures in sign language. For both groups, representational momentum occurred for signs in the normal direction of movement and for signs in the reversed direction of movement, and displacement was larger for signs in the normal direction. In a set of control experiments, Wilson et al. found that these differences appeared to be due to biomechanical constraints on motion (referred to as an *awkwardness effect*), rather than to learned motion patterns per se, and they suggested that there might be resistance to representational momentum for participants fluent in sign language. Indeed, just as verbal consonants are categorically perceived, so too might gestural signs be categorically perceived, and such categorical perception would obscure any potential representational momentum. Such a suggestion (1) is consistent with Freyd's (1993) speculation that representational momentum occurs for stimuli based on continuous dimensions but not for stimuli based on categorical dimensions and (2) accounts for the lack of a fluency effect that might have been predicted on the basis of increases in displacement typically found with increases in expertise (e.g., Blättler, Ferrari, Didierjean, & Marmèche, 2011; Blättler, Ferrari, Didierjean, van Elslande, & Marmèche, 2010). Also, an influence of biomechanical constraints on representational momentum for the body is consistent with demonstrations of other object-specific constraints (e.g., Nagai & Yagi, 2001; Reed & Vinson, 1996; Vinson & Reed, 2002).

Jarraya, Amorim, and Bardy (2005) presented a computer-generated point-light character engaged in a backflip movement, and in some conditions, the point-light character was presented on a textured surface that provided additional information about spatial layout. The movement was interrupted at different points, and participants compared the final position of the target with a probe character. The participants' viewpoint was static or corresponded to a panning or tracking camera movement (cf. effects of camera movement in Brown & Munger, 2010; Munger et al. 2006). The patterns of optic flow differed for different viewpoints or camera movements; Jarraya et al. suggested that in the absence of optic flow involving translation or rotation of the target, representational momentum would not occur. If the textured surface was present, representational momentum occurred in all conditions, but if the textured surface was not present, representational momentum occurred only in the static viewpoint condition. Jarraya et al. suggested that the lack of representational momentum in other conditions reflected use of landmarks in the spatial layout to disambiguate target position. However, it is difficult to reconcile Jarraya et al.'s views regarding optic flow with findings that representational momentum occurs in memory for frozen-action photographs (which do not necessarily provide optic flow information) and demonstrations that participants possess sufficient information about body movement to extrapolate body motion in the absence of other spatial context (e.g., Shiffrar & Freyd, 1990; Verfaillie & Daems, 2002).

Modality

At the time of Hubbard's (2005) review, the majority of studies in the representational momentum literature involved visual stimuli. Several studies examining representational momentum for auditory stimuli have subsequently appeared. Getzmann and Lewald (2007) measured displacement of a moving auditory target at different points during the target's trajectory. During the initial, middle, or final portion of the trajectory, participants received a tactile cue to indicate the currently perceived location of the auditory target. The judged location was displaced forward during the initial portion of the trajectory (consistent with a Fröhlich effect), not displaced during the middle of target motion, and displaced forward after the target vanished (consistent with representational momentum). Getzmann and Lewald (2007) suggested that representational momentum occurs only when the target vanishes and is not a continuous extrapolation during target motion along the entire length of the trajectory. Getzmann and Lewald (2009) presented visual targets or auditory targets moving horizontally, and targets maintained a constant velocity or an irregularly changing velocity. There was no effect of modality on representational momentum, but there was a trend for displacement for auditory targets to decrease more with irregular velocities (cf. smaller displacement with irregular visual directions; Kelly & Freyd, 1987). Getzmann (2005) reported that oculomotor behavior did not influence representational momentum for the location of a moving sound source.

Johnston and Jones (2006) presented auditory targets involving inducing stimuli consisting of a sequence of discrete auditory tones of different pitches (and so movement was through auditory frequency space, rather than through physical space). If a target consistently ascended or descended in pitch, memory for the final pitch was displaced in the direction of pitch motion. If a target oscillated between a high pitch and a low pitch (i.e., a sequence of descending pitches immediately followed by a sequence of ascending pitches immediately followed by a sequence of descending pitches, etc.), memory for the final pitch was displaced in the anticipated direction of the next tone. More specifically, if a target ended midway between the highest pitch and the lowest pitch, displacement for the final pitch was in the direction of previous pitch motion, whereas if a target ended on the highest pitch or on the lowest pitch (and so would have reversed direction had target motion continued), displacement for the final pitch was in the direction opposite to previous pitch motion but consistent with the next expected pitch. If inducing stimulus tones did not consistently ascend, descend, or oscillate but were presented in a random order, systematic displacement in memory for the final pitch did not occur. These results were consistent with previous findings on the effects of expectancies on representational momentum for visual stimuli (Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991).

Schmiedchen et al. (2013) presented auditory targets (noise bursts 250–1000 or 2000–8000 Hz) or visual targets (point light sources) that moved leftward or rightward. Forward displacement for auditory targets and for visual targets increased as the vanishing point moved from central to paralateral regions and then decreased as the vanishing point moved from paralateral into lateral (peripheral) regions (and was negative in the extreme periphery). Visual displacement was dependent upon velocity and vanishing point, whereas auditory displacement was dependent upon velocity, vanishing point, and direction. However, Schmiedchen et al. (2013) presented only leftward and rightward motion; if they had presented ascending and descending motion, an effect of direction for visual targets would likely have occurred (cf. Hubbard, 1990; Hubbard & Bharucha, 1988). Differences between visual displacement and auditory displacement were most pronounced at more peripheral vanishing points, and Schmiedchen et al. (2013) suggested that this reflected the greater decrease in localization acuity for visual stimuli than for auditory stimuli in the periphery. Schmiedchen et al. (2013) also suggested that representational momentum reflected an interplay between modality-specific processing of motion parameters (e.g., vanishing point location, velocity, direction) and high-level predictive mechanisms, and this is consistent with Hubbard's (2005, 2006b) suggestion that representational momentum reflected a combination of high-level and low-level processes and information.

Display

Effects of characteristics of the display on representational momentum have not received much recent investigation. Findings considered here involve (1) surface form of the target, (2) retention interval, (3) prior probability that a *same* response to a probe would be correct, and (4) contrast between the target and the background.

Surface form

The surface form of a target involves the type of motion the target exhibits, and three types of surface form have been used in studies of representational momentum: implied (discrete) motion, smooth (continuous) motion, and frozen-action photographs (see Hubbard, 2005).[2] Two recent studies involving frozen-action photographs found evidence that motion is extrapolated from such stimuli. Although neither study explicitly considered representational momentum, their results are consistent with the claim that representational momentum occurs

[2] Implied motion involves a set of spatially and temporally discrete stimuli that change in position over space and time in a digital fashion (e.g., the set of inducing stimuli in the top panel of Fig. 1), and continuous (smooth) motion involves the appearance of a target that moves through space and time in a continuous and analogue fashion (e.g., real object motion or apparent motion). Frozen-action photographs involve a stimulus at a specific moment in time and usually involve a moment from within a longer motion sequence (e.g., a dancer in mid-leap). Whether or not representational momentum occurs with each type of surface form, and differences in the magnitude of representational momentum between targets with different surface forms, has significant theoretical importance. For example, neither implied motion of a target nor a single frozen-action photograph evoke smooth pursuit eye movements, and so the presence of representational momentum for such stimuli is evidence that representational momentum does not necessarily depend upon ocular overshoot due to smooth pursuit eye movements (see discussions in Hubbard, 2005, 2006b, 2010).

with static stimuli that include motion information. Winawer, Huk, and Boroditsky (2008) presented participants with a sequence of frozen-action photographs in which depicted motion was always in the same direction. A probe consisting of a set of moving dots was then presented; coherence of motion varied, and participants indicated the global direction of dot motion. Participants were more likely to judge the dots as moving in the direction opposite to the direction suggested in the frozen-action photographs (cf. Nagai & Saiki, 2005). Pavan, Cuturi, Maniglia, Casco, and Campana (2011) adapted participants to a single direction of motion using frozen-action photographs, and then they presented a stationary Gaussian dot. The perceived position of the dot was shifted in the direction opposite to the direction suggested in the frozen-action photographs. The findings of Winawer et al. and of Pavan et al. are consistent with the presence of a motion aftereffect, and this suggests that frozen-action photographs activate direction-selective circuits involved in processing actual motion. Activation of such circuits is consistent with the presence of representational momentum in such stimuli.

Retention interval

De sá Teixeira, Hecht, and Oliveira (2013) presented targets that exhibited smooth horizontal motion, and participants positioned a subsequently presented cursor at the final location of the target. Latency between when the target vanished and when the cursor appeared varied. Forward displacement (i.e., representational momentum) peaked between 150 and 300 ms after the target vanished and then declined if participants were allowed to track the targets, and this is consistent with previous findings. Interestingly, downward displacement (i.e., representational gravity; Hubbard, 1990, 1995c, 1997) of the remembered vanishing point of the target increased with increases in latency of appearance of the cursor (up to 1,200 ms) and was not influenced by whether participants were allowed to track the moving target or fixated a stationary point away from the path of the moving target. De sá Teixeira, Hecht, and Oliveira suggested that these patterns were consistent with an impetus-like trajectory (cf. Kozhevnikov & Hegarty, 2001); such a pattern is also consistent with the hypothesis that displacement reflects subjective aspects of physical principles, rather than objective physical principles per se (Hubbard, 2005, 2006a, 2006b, 2013a, 2013c). However, use of a cursor-positioning methodology confounded effects of retention interval with effects of the time required to locate and move the cursor, and time to locate and move the cursor could vary widely from trial to trial. How such a confound might have influenced apparent effects of retention interval is not clear.

Prior probabilities

Hubbard and Lange (2010) presented targets that exhibited implied leftward or rightward motion, and participants judged whether a subsequently presented probe was located at the final location of the target. In one experiment, different groups of participants were presented with trials in which the prior probability that a *same* response would be correct was 10 %, 30 %, 50 %, 70 %, or 90 %. Participants were not informed of these probabilities. Representational momentum was not influenced by prior probabilities, but participants were less likely to respond *same* when the prior probability was lower. Increases in the actual prior probability a *same* response would be correct across participants did not influence hit rates, but did increase false alarm rates and, for participants who experienced the highest prior probability, decreased d' and increased β. In a second experiment, all participants were presented with the same set of stimuli (in which the prior probability that a *same* response would be correct was 11 %), but different groups of participants were instructed that a *same* response would be correct on 10 %, 30 %, 50 %, 70 %, or 90 % of the trials. Representational momentum was not influenced by prior probabilities, but participants were less likely to respond *same* when they believed that the prior probability a *same* response would be correct was lower. Increases in the expected prior probability a *same* response would be correct across participants increased hit rates, increased false alarm rates, and decreased β, but did not influence d'.

Contrast

Representational momentum for luminance of a target that changed in luminance was previously investigated (Brehaut & Tipper, 1996), but effects of target luminance and of contrast between target luminance and background luminance on representational momentum for location were only recently investigated. Although not explicitly addressing representational momentum, Maus and Nijhawan (2006) presented a smoothly moving target on a dark background. If target luminance (and contrast of the target with the background) gradually decreased with increases in target motion, forward displacement was larger than if the target traveled a shorter distance and abruptly vanished. Maus and Nijhawan (2009) measured displacement of a target that decreased in contrast with the background or vanished shortly after a nontarget stimulus was briefly displayed, and they suggested that weaker motion signals (resulting from less contrast) led to smaller forward displacement. However, this conclusion appears inconsistent with Kerzel's (2003b) suggestion that weaker motion signals (resulting from less continuous motion) led to larger forward displacement. Hubbard and Ruppel (2014) presented a light or a dark target that exhibited implied horizontal motion on a white or black background, and targets (1) maintained a constant contrast with the background or (2) increased or decreased in contrast with the background. Representational momentum for target location was larger with high or increasing contrast than with low or decreasing contrast, and final contrast, rather than initial or mean contrast, was most closely related to magnitude of representational momentum.

Context

Recent studies of effects of characteristics of the context on representational momentum examined new types of context, as well as types of context previously considered. Findings considered here involve (1) shading and shadows, (2) crossmodal information, (3) nontarget stimuli, (4) scenes, (5) causality, and (6) other (nonmomentum) implied physical principles.

Shading and shadows

Hidaka, Kawachi, and Gyoba (2009) used representational momentum to investigate depth properties of apparently moving 3-D objects, and they used shape from shading to suggest depth information. In one experiment, the first and third inducing stimuli (initial and final portions of target motion) were convex or concave, and the second inducing stimulus (middle portion of target motion) was convex, concave, or flat. If the first and third inducing stimuli were convex, forward displacement was larger if the second inducing stimulus was flat rather than concave. In a second experiment, convex and concave stimuli were replaced with luminance-polarized circles (e.g., a luminance-polarized circle in which the top half is white and the bottom half is black is equivalent to a convex stimulus illuminated from the top). Identity of the second inducing stimulus did not influence displacement, and this suggested luminance information was not responsible for the pattern of data in the first experiment. In a third experiment, the first and third inducing stimuli were convex, and the second inducing stimulus was a blurred convex stimulus or a concave stimulus. Hidaka et al. interpreted their results as demonstrating that internal representations of moving 3-D objects contain coarse depth information intermediate between 2-D and 3-D, particularly regarding convexity involving low-spatial-frequency information. As will be discussed below, Taya and Miura (2010) reported that an apparent cast shadow can influence representational momentum for a target.

Crossmodal information

One area in representational momentum literature that has recently attracted attention from researchers is the possible influence of crossmodal information on representational momentum. In some cases, it is difficult to determine whether this is an effect of context per se or an effect of the multisensory nature of a single target. Since judgment of a potentially multisensory target typically involves only one of the modalities of that target on a given trial, the nonjudged modalities can be considered as (different modality) context. Hubbard and Courtney (2010) presented a visual target (a square) that ascended or descended in the picture plane concurrent with an auditory target (a tone) that ascended or descended in frequency space (pitch). Motions of visual targets and of auditory targets were congruent (i.e., both ascending or both descending) or incongruent (i.e., one ascending and one descending). A probe for final visual location in the picture plane or for final auditory pitch in frequency space was then presented. Auditory representational momentum was larger if visual motion was congruent with auditory motion, but visual representational momentum was not influenced by the congruency of auditory motion. Horizontal visual motion was then paired with auditory motion that ascended or descended in pitch, and representational gravity (downward displacement) of the visual target was larger if auditory motion descended than if auditory motion ascended.

Teramoto, Hidaka, Gyoba, and Suzuki (2010) presented a horizontally moving visual target and an auditory tone of a constant frequency. If the tone began at the same time as visual target motion, representational momentum for the visual target decreased or increased if the tone terminated slightly before or after, respectively, the visual target vanished. Representational momentum for the visual target was not influenced by the tone if the tone was briefly presented before or after visual target offset or if onset of the tone was not synchronized with onset of visual motion. Teramoto et al. suggested that a close association between auditory signals and visual signals (accomplished by onset synchrony) is necessary in order for auditory information to modulate visual representational momentum. Chien, Ono, and Watanabe (2013) presented a brief auditory tone proximal to the offset of a visually moving target, and if the tone was presented slightly before visual target offset, displacement was backward. If the tone was presented to only the left ear or the right ear, backward displacement was larger if the tone was on the same side of space where visual motion originated. Chien et al. interpreted this as evidence against the modality precision hypothesis (i.e., the modality with the highest precision for a specific task is dominant in multimodal interactions; see, e.g., Welch & Warren, 1980), and they suggested that perceived timing of visual offset was attracted toward timing of the transient sound. However, direction of motion within left or right visual fields and perceived location of sound were not crossed; although suggestive, the data do not rule out alternative explanations.

Schmiedchen et al. (2012) presented a moving visual target and a concurrent moving auditory target, and participants used a pointer to indicate the vanishing point location of the visual target or the auditory target. The disparity between the vanishing point of the auditory target and the vanishing point of the visual target varied. For short target durations (500 ms), negative disparity (i.e., the nonjudged modality vanished before the judged modality vanished) resulted in backward displacement, and positive disparity (i.e., the nonjudged modality vanished after the judged modality vanished) resulted in forward displacement, and such a pattern is consistent with Teramoto et al. (2010). Additionally, auditory displacement was more likely to be modulated by visual information if targets vanished in central rather than in peripheral regions, and visual displacement was more likely to be modulated by auditory information if targets vanished in peripheral rather than in central regions; Schmiedchen et al. (2012) suggested that this was due to differences in localization acuity for visual and auditory stimuli in different regions. With longer durations (2,000 ms), an effect of disparity occurred only when participants indicated the vanishing point of auditory targets, and this is similar to Hubbard and Courtney's (2010) finding that auditory forward displacement, but not visual forward displacement, was influenced by congruency of visual or auditory motion, respectively (also, targets in Hubbard and Courtney, 2010, were limited to the central region).

Nontarget stimuli

Previous research demonstrated that the presence of other (nontarget) stimuli could influence target displacement (e.g., Hubbard, 1993; Hubbard et al., 2001; Hubbard & Ruppel, 1999, 2000, 2002), and as was discussed above, crossmodal information in a multisensory target could be considered as nontarget context, and so findings of Chien et al. (2013), Hubbard and Courtney (2010), Schmiedchen et al. (2013), and Teramoto et al. (2010) also demonstrate influences of nontarget stimuli on the representational momentum of a target. Hubbard (2008) turned this notion around and examined whether the presence of a moving target could influence potential displacement of other stimuli. A briefly presented stationary object was aligned with the final position of a horizontally moving target and visible during presentation of the final inducing stimulus. Participants indicated the location of the stationary object or the final location of the target. Memory for the location of the stationary object was displaced in the same direction as memory for the final location of the moving target, and this displacement (1) decreased with increases in vertical distance of the stationary object from the final target location and (2) exhibited a time course similar to that previously shown for representational momentum. Displacement of the stationary object was suggested to reflect spreading activation from the representation of the target to the representation of the stationary object, and this spreading activation weakened with distance and began decaying as soon as the target vanished.

Nagai and Saiki (2005) attempted to dissociate effects on displacement of perceived motion and of actual motion by presenting nontarget stimuli that they hypothesized would induce illusory motion of the target. In one experiment, a target descended or ascended while also moving toward the right, and on some trials, two other stimuli (one above the target, one below the target) were also presented and moved toward the right, and all three stimuli remained vertically aligned. Judgment of target direction, but not displacement, was influenced by the two other stimuli. In a second experiment, a rightward-moving target was presented against a backdrop of dots that was stationary, moved in the direction of target motion, or moved in the direction opposite to target motion. Judgment of velocity, but not displacement, was influenced by behavior of the background. Nagai and Saiki argued that displacement depended on actual motion, rather than on perceived motion. Hubbard and Ruppel (2013a) examined displacement for the line in illusory line motion (i.e., a cue is presented immediately before an adjacent line appears, but even if the entirety of the line appears simultaneously, the line is perceived to unfold or be drawn from the end closest to the cue to the end most distant from the cue; e.g., Hikosaka, Miyauchi, & Shimojo, 1993). Hubbard and Ruppel (2013a) hypothesized that the line might be displaced away from the cue and in the direction of illusory motion; however, memory for the line was displaced toward the cue. The results of Nagai and Saiki and of Hubbard and Ruppel (2013a) suggest that illusory motion does not influence representational momentum of a visual target.

Taya and Miura (2010) presented horizontal motion of a target and that target's apparent cast shadow. Motion of the cast shadow converged with, paralleled, or diverged from the path of the target. Control conditions involving presentation of only the target, or in which the target and cast shadow switched trajectories, were also presented. Forward displacement was larger if paths of the target and cast shadow diverged, and this was interpreted as reflecting motion toward the observer (cf. Hubbard, 1996; Nagai, Kazai, & Yagi, 2002). Downward displacement was larger if the paths of the target and cast shadow converged, and this was interpreted as reflecting downward motion. Although the target always moved horizontally, different patterns of displacement with different types of cast shadows were perceived as different directions of motion. Taya and Miura suggested that the visual system uses information from cast shadows to predict the future location of a moving target. Taya and Miura argued that displacement depended on perceived motion rather than on retinal motion (cf. displacement in frozen-action photographs), and this suggests that illusory motion can influence displacement. Relatedly, Hubbard, Ruppel, and Courtney (2005) reported illusory gamma motion from a nontarget stimulus that appeared adjacent to a previously stationary target that then began moving could influence representational momentum for that target. Results of Taya and Miura and of Hubbard et al. (2005) suggest that illusory motion can influence representational momentum of a visual target, but the reason for apparent inconsistencies of these data with Nagai and Saiki (2005) and Hubbard and Ruppel (2013a) is not clear.

Scenes

Many early studies of representational momentum presented targets on a blank background. Several recent studies examined targets embedded within a scene, and some of these recent studies also addressed the relationship between boundary extension (i.e., a bias in which a previously viewed scene is remembered as containing information that might have been present just beyond the boundaries of the original view; for a review, see Hubbard, Hutchison, & Courtney, 2010) and representational momentum. Munger, Owens, and Conway (2005) presented inducing stimuli that implied motion of the self into a scene along the line of sight, and they measured representational momentum for the final viewpoint and boundary extension for the scene. Boundary extension and representational momentum each occurred but did not interact, and Munger et al. (2005) suggested that boundary extension and establishment of spatial layout occur prior to representational momentum of targets within that spatial layout (cf. Jarraya et al., 2005). Such a suggestion is consistent with findings that representational momentum takes a few hundred milliseconds to peak (for a review, see Hubbard, 2005), but boundary extension occurs within a few dozen milliseconds (Dickinson & Intraub, 2008). DeLucia and Maldia (2006) presented motion along the line of sight toward a target, and they reported that memory for the boundaries of the final view was not consistent with representational momentum for the self. Neither Munger et al. (2005) nor DeLucia and Maldia addressed which aspects of a scene might influence representational momentum of the self in the scene, and both Munger et al. (2005) and DeLucia and Maldia concluded that representational momentum and boundary extension were separate processes.[3]

Munger et al. (2006) examined whether (1) assessing representational momentum of targets embedded in a scene could aid in learning the spatial layout of that scene and (2) explicit knowledge of the spatial layout of a scene could influence representational momentum for targets in that scene. Munger et al. (2006) presented scenes in which the camera (self) appeared to rotate to the left or right (resulting in movement of an otherwise static target [e.g., bench, tree] toward the right or left, respectively). Representational momentum was larger for targets entering the scene than for targets exiting the scene, and this might reflect increased sensitivity for entering (approaching) targets or an interaction of representational momentum with boundary extension (if targets enter a scene, representational momentum and boundary extension operate in the same direction [increasing context behind the trailing edge of the target], whereas if targets exit a scene, representational momentum and boundary extension operate in opposite directions and partially cancel). Camera rotation across the scene led to representational momentum for targets even though movement involved the viewpoint (self) and not the targets per se (i.e., environment-centered coordinates of targets did not change). Participants who had not viewed a map of the scene before beginning the localization task could not correctly choose between a correct map and a mirror-image map of the scene after the localization task was completed. However, if participants were asked about spatial layout during the localization task (e.g., what is to the left?), learning of spatial layout was enhanced.

Brown and Munger (2010) presented participants with one of three camera views relative to an island scene (consisting of a lighthouse in the middle of the island and a palm tree, beached boat, boat dock, and beach umbrella spaced along the perimeter of the island). Camera views involved rotation (targets appeared to translate across the view), combined translation + rotation (targets remained centered in the view as the camera moved), or aerial views (from the top of the lighthouse). Representational momentum occurred in all conditions. Forward displacement was smaller if participants were presented with translation + rotation than with rotation, and Brown and Munger suggested that rotation was easier to extrapolate than was translation + rotation (since translation + rotation, but not rotation, involved changes in the portrayed depths of targets); also, smaller representational momentum with translation + rotation is consistent with previous findings of smaller forward displacement for more complex rotation in depth (Munger, Solberg, & Horrocks, 1999). Participants subsequently given a surprise test of memory of spatial layout performed above chance in choosing a correct map only if they had been presented with aerial views during the representational momentum task. Brown and Munger interpreted this as suggesting that object–location binding is viewpoint specific. An alternative but related possibility involves encoding specificity, since aerial maps presented during testing more closely resembled aerial views presented during the localization task.

[3] An explicit comparison of representational momentum and boundary extension is provided in Hubbard et al. (2010), who suggested that representational momentum and boundary extension might be related (e.g., boundary extension [Intraub, 2002] and representational momentum [Freyd, 1987] depend upon continuity of the underlying stimulus; boundary extension [Intraub, Daniels, Horowitz, & Wolfe, 2008] and representational momentum [Hayes & Freyd, 2002] increase under divided attention; boundary extension [Intraub, Hoffman, Wetherhold, & Stoehs, 2006] and representational momentum [Jordan & Hunsinger, 2008] are influenced by action plans; and boundary extension [Intraub & Bodamer, 1993] and representational momentum [Courtney & Hubbard, 2008] are reduced but not eliminated if participants are given explicit instructions about the effect and are asked to guard against it in their responses).

Causality

Hubbard et al. (2001; Hubbard & Favretto, 2003; Hubbard & Ruppel, 2002) reported that representational momentum of targets in launching effect displays was decreased relative to representational momentum of several types of nonlaunched control targets, and they suggested that representational momentum might be related to perception of causality. Choi and Scholl (2006) replicated the decreased forward displacement for launched targets, relative to the nonlaunched control targets used by Hubbard et al. (2001), and they also reported that displacement of launched targets did not differ from displacement of targets in a nonlaunching "passing" condition (although the latter condition was not compared with other control conditions). Choi and Scholl suggested that the decrease in representational momentum for launched targets reflected the presence of two objects and a single motion, rather than a perception of causality. Hubbard (2013a) tested this hypothesis by comparing displacement of targets in displays based on the entraining effect (i.e., a launcher contacts a target and continues in the same direction and velocity after contact and appears to carry the target along; Michotte, 1946/1963) and targets in displays based on the launching effect. The entraining effect and the launching effect each involve two objects and a single motion, and so displacement of the target should have been similar for the two conditions; however, displacement of the target on entraining effect trials was larger than displacement of the target on launching effect trials.

De sá Teixeira et al. (2008) presented a launching effect display in which the launcher varied in size (implied mass) and in velocity. Participants were told that only the initial portion of the target trajectory was visible, and they were asked to provide a numerical rating of how much further the target would have traveled. Displacement for the last viewed location of the target was also measured. Increases in launcher size or in launcher velocity led to larger representational momentum for the last viewed location of the target and to higher numerical ratings (i.e., judgments of greater distances), and effects of size and effects of velocity were additive (cf. de sá Teixeira, Pimenta, & Raposo, 2013). De sá Teixeira et al. (2008) suggested that forward displacement reflects joint action of different variables relevant to causal perception (cf. joint action of variables in "noncausal" displays—e.g., momentum and friction, Hubbard, 1995b; momentum and gravity, Hubbard, 1990, 1997), and they provided a useful demonstration of the relationship between subjective reports of phenomenology (numerical ratings) and a more objective behavior (displacement in judged location). The findings of de sá Teixeira et al. (2008) are consistent with claims that perception of launching involves an impression that impetus or other force is imparted from the launcher to the target in a launching effect (e.g., Hubbard, 2004, 2013a, 2013c; P. A. White, 2007, 2009, 2012). The relationship of representational momentum to perception of causality is discussed in more detail in Hubbard (2013a, 2013c).

Other physical principles

The only nonmomentum physical principle investigated in recent representational momentum literature is gravity. Hubbard (1990, 1995c, 1997, 2005) suggested that representational gravity could combine with representational momentum, and the framework he suggested assumed that effects of momentum were independent of effects of gravity. Motes, Hubbard, Courtney, and Rypma (2008) tested this independence by presenting rightward-moving targets and carrying out a principal components analysis on the displacements. Effects of implied momentum and effects of implied gravity loaded on separate components, and this supported the hypothesis that implied momentum and implied gravity exert separate influences on spatial memory. De sá Teixeira, Hecht, and Oliveira (2013) reported that the effects of retention interval and oculomotor behavior on representational gravity were different from the effects of retention interval and oculomotor behavior on representational momentum. They concluded that forward displacement and downward displacement were mutually exclusive for horizontally moving targets, and this conclusion is consistent with Motes et al. (2008). De sá Teixeira, Hecht, and Oliveira also concluded that there was an internalization of gravity in representation of motion. Internalization of a physical principle such as gravity lends credence to the possibility of internalizations of other physical principles (e.g., momentum, friction, centripetal force; see Hubbard, 1995c, 2005; but for dissenting views, see Hecht, 2001; Kubovy & Epstein, 2001).

Other researchers have recently reported evidence consistent with representational gravity. De sá Teixeira, Pimenta, and Raposo (2013) reported that schizophrenia patients and control participants exhibited larger displacement for descending motion than for ascending motion, and as was noted earlier, Taya and Miura (2010) found larger downward displacement if cast shadows suggested that targets were moving downward than if cast shadows suggested that targets were moving upward. Other researchers have also recently reported evidence inconsistent with representational gravity. Actis-Grosso et al. (2008) did not find larger displacement for descending motion than for ascending motion, but their target was small (a dot 5 pixels in diameter); one speculative possibility is that such a small target possessed so little implied mass that gravitational effects were negligible. Lenggenhager et al. (2012) reported no difference in displacement for ascending motion and displacement for descending motion in neglect patients or control participants. When representational gravity of a moving target is measured, the magnitude of that representational gravity is usually much smaller than the magnitude of representational momentum for that target. Also, it should be noted that although most studies of representational gravity involved moving targets, effects of representational gravity have been found for displacement of stationary targets (e.g., Freyd, Pantzer, & Cheng, 1988; Hubbard & Ruppel, 2000).

Observer

Hubbard (2005) noted that effects of characteristics of the observer on representational momentum had received relatively little study, and several studies on effects of characteristics of the observer on representational momentum have subsequently appeared. Findings considered here involve (1) age, (2) attention, (3) eye movements, (4) expertise, (5) knowledge and feedback regarding representational momentum, (6) action plans, and (7) psychopathology.

Age

Perry, Smith, and Hockema (2008) presented children 24 to 32 months old with a display in which a toy car rolled down a ramp and vanished behind an occluder. Children could then open one of four doors along the length of the occluder to retrieve the car, and they were more likely to choose a door beyond where the car would have stopped (i.e., a door further in the direction of motion), especially if the car traveled at a faster velocity. Perry et al. suggested that this was evidence of representational momentum. Taylor and Jakobson (2010) presented children 5 to 9 years old with displays similar to Finke and Freyd's (1985) implied motion displays. Older children exhibited larger representational momentum than did younger children, and curiously, children who had been born preterm exhibited smaller representational momentum than did children who had been born at full term. Taylor and Jakobson noted that larger representational momentum with older children initially appears inconsistent with previous findings, but they suggested that this resulted from differences in stimuli (e.g., Hubbard, Matzenbacher, & Davis, 1999, reported larger forward displacement in 5-year-old children than in adults, but they presented smooth horizontal or vertical motion, whereas Taylor and Jakobson presented implied rotational motion; younger children might be less sensitive to implied motion than to continuous motion, or mechanisms for processing linear motion might mature before mechanisms for processing rotational motion).

Piotrowski and Jakobson (2011) reported that older adults (65 years or older) exhibited less representational momentum for targets exhibiting implied rotation than did younger adults who were matched on education, global functioning, and crystallized intelligence. Inspection of their Fig. 1 suggests larger differences between younger adults and older adults for backward probes than for forward probes, and the distribution of *same* responses was flatter for older adults than for younger adults. Thus, the apparent decrease in representational momentum might reflect an increased inability to reject negative probes or a more general insensitivity, rather than a decrease in forward displacement. If older adults were divided into "younger-old" and "older-old" groups, neither group exhibited representational momentum, but there was a trend for forward displacement in the younger-old group. Piotrowski and Jakobson suggested that the apparent lack of representational momentum in older adults might reflect an inability to process implied motion accurately, and this predicts that differences in representational momentum between older adults and younger adults might not be found if stimuli consisted of continuous motion targets or frozen-action photographs. As Piotrowski and Jakobson noted, older adults exhibit slower mental rotation velocities (e.g., Dror & Kosslyn, 1994), and so their findings are consistent with the correlation between velocity of mental rotation and magnitude of representational momentum for rotating targets reported by Munger et al. (1999).

Attention

Hubbard, Kumar, and Carp (2009) examined effects of cuing the final location of the target on representational momentum of horizontally moving targets. In one experiment, a cue was present during the entirety of target motion on some trials and was of high relevance (i.e., indicated horizontal and vertical final location of the target) or low relevance (i.e., indicated horizontal, but not vertical, final location of the target). Representational momentum decreased if a cue was presented and decreased more if cue relevance was high. In subsequent experiments, presentation of a (high-relevance) cue during the final portion of target motion (concurrent with the final inducing stimulus), during the retention interval between disappearance of the target and appearance of the probe, or during both the final portion of target motion and the retention interval all decreased forward displacement. In no condition did presentation of a cue eliminate representational momentum, and this is consistent with the hypothesis that at least one component of representational momentum is modular (i.e., not influenced by knowledge, beliefs, or expectations; e.g., Courtney & Hubbard, 2008; Hubbard, 2005, 2006a, 2006b; Ruppel, Fleming, & Hubbard, 2009). However, cues presented during the final portion of target motion or during the retention interval might have been displaced in the direction of target motion (cf. displacement of stationary objects near the target in Hubbard, 2008) and so might not have been effective in indicating the actual final location of the target.

Eye movements

Some studies reported that if participants were not allowed to visually track a smoothly moving target, representational momentum for that target was decreased or eliminated (e.g., de sá Teixeira, Hecht, & Oliveira, 2013; Kerzel, 2000), and this led to suggestions that forward displacement was due to pursuit eye movements overshooting the final target position and to visual persistence (e.g., Stork & Müsseler, 2004). De sá Teixeira, Hecht, and Oliveira (2013) suggested that constraining eye movements could "be taken to suppress or conceal the effects of motion representations that normally drive eye movements (and our memory for location)" (p. 1697). The idea that constraining eye movements can suppress or conceal effects of motion representation implies that displacement is generated by a mechanism other than eye movements (that would be suppressed or concealed), and so this is consistent with Hubbard's (2005, 2006b, 2010) argument that overshooting of the final position of the target by smooth pursuit movements is not solely or ultimately causal of representational momentum even if oculomotor behavior modulates forward displacement of smooth motion targets (because representational momentum is also found if targets exhibit implied motion and in memory for a single frozen-action photograph, neither of which involves smooth pursuit eye movements). Also, de sá Teixeira, Hecht, and Oliveira reported that eye movements were not related to downward displacement (representational gravity) for horizontally moving targets.

Several reports challenge the claim that preventing visual tracking of smoothly moving visual targets eliminates representational momentum. Getzmann and Lewald (2009), Teramoto et al. (2010), and Schmiedchen et al. (2013) reported representational momentum when participants were not allowed to track a smoothly moving visual target. Getzmann and Lewald (2009) monitored eye movements to ensure compliance with instructions to fixate or track the target, and eye movement instruction was not significant. Neither Teramoto et al. nor Schmiedchen et al. (2013) monitored eye movements, but they asked participants to maintain fixation on a single point or to maintain gaze straight ahead, respectively. It is possible that participants disobeyed instructions and tracked the target, but this seems unlikely (e.g., if participants tracked targets in Schmiedchen et al., 2013, target eccentricity should not have influenced displacement). Getzmann and Lewald (2009) and Teramoto et al. suggested that their data contradicted Kerzel (2000), and Schmiedchen et al. (2013) suggested that forward displacement is independent of eye movements. De sá Teixeira, Pimenta, and Raposo (2013) reported that schizophrenia patients exhibited representational momentum for smoothly moving targets, but eye movements were not monitored. Given that the majority of such patients exhibit dysfunction of pursuit eye movements (for a review, see O'Driscoll & Callahan, 2008), it is unlikely that representational momentum in those patients resulted from pursuit eye movements. As was noted earlier, Getzmann (2005) reported that oculomotor behavior did not influence representational momentum for the location of a moving sound source.

Expertise

Blättler et al. (2010) presented expert drivers and novice drivers with displays involving roadway scenes filmed by a camera onboard a moving automobile. The scenes were briefly interrupted, and after the interruption, resumed slightly before the point of interruption, at the point of interruption, or slightly after the point of interruption; participants judged whether the display resumed at the point where the interruption occurred (cf. Thornton & Hayes, 2004). All participants exhibited representational momentum, and representational momentum was larger for expert drivers. When tested on control stimuli involving a running person or a moving geometric object, all participants exhibited representational momentum, but there was no difference between expert drivers and novice drivers. Effects of expertise on representational momentum were domain specific, and this suggests that displacement is based on expectations or predictions regarding future target behavior, since experts would have more or stronger expectations and predictions than would novices. Blättler et al. (2011) presented displays involving aircraft landings (as viewed from inside an aircraft cockpit) to expert pilots and to control participants with no flight training experience. The display was briefly interrupted, and participants judged whether the display resumed at the point where the interruption occurred. Expert pilots exhibited representational momentum, but control participants did not exhibit displacement. Blättler et al. (2011) attributed the lack of displacement in control participants to a lack of familiarity with the stimuli.

Knowledge and feedback

Courtney and Hubbard (2008) presented participants with targets consisting of inducing stimuli that moved leftward or rightward. One group of participants, the "uninformed" group, was asked to observe the target and, when the probe appeared, to judge whether the probe was at the same location where the target vanished or at a different location. A second group, the "informed" group, was given the same instructions as the uninformed group and was also instructed regarding previous findings on representational momentum. The third group, the "counteract" group, was given the same instructions as the informed group and was also asked to counteract and compensate for representational momentum in their responses. Representational momentum occurred in all groups and was larger in the uninformed group than in the other groups. Ruppel et al. (2009) presented implied horizontal motion and had participants judge whether a subsequently presented probe was at the same location as the final target location, and in some conditions, verbal feedback (the printed word "correct" or "error") was given after each judgment. Whether or not feedback was given did not influence the magnitude of representational momentum, although feedback did decrease the general likelihood of a *same* response (for a discussion, see Hubbard & Lange, 2010). Thus, explicit knowledge regarding the existence of representational momentum or the accuracy of previous responses does not eliminate forward displacement.

Action plans

Jordan and Hunsinger (2008) presented pairs of participants with displays in which a target moved horizontally back and forth (see also Jordan & Knoblich, 2004). Target motion was under the control of one participant, the controller (who was responsible for reversing target direction within narrow turning areas near the left and right edges of the display), and motion was controlled by pressing a left key (which increased velocity of leftward motion or decreased velocity of rightward motion) or a right key (which increased velocity of rightward motion or decreased velocity of leftward motion). The target vanished after three or four reversals. The other participant, the observer, watched the display and, after the target vanished, indicated the final location of the target. After one block of trials, participants exchanged roles, and another block of trials was presented. Observers in block 2 (who had experience controlling the target in block 1) exhibited larger forward displacement than did observers in block 1 (who did not have experience controlling the target). Jordan and Hunsinger included several control conditions to rule out alternative hypotheses (e.g., a new controller was brought in for block 2, observers could see or not see controllers' actions during block 1, etc.). In general, knowledge of the actions involved in previously controlling the target increased forward displacement, even though participants were not controlling the target when it vanished. This is consistent with findings of larger representational momentum for observed stimuli in a domain of expertise (e.g., Blättler et al., 2011; Blättler et al., 2010).

The increase in forward displacement for participants with prior experience in controlling the target in Jordan and Hunsinger (2008) initially seems inconsistent with the findings of Jordan and Knoblich (2004) and Jordan, Stork, Knuf, Kerzel, and Müsseler (2002) that participants exhibited decreased representational momentum (or negative displacement) if those participants had more control of the target. However, Jordan and Hunsinger did not compare displacements exhibited by controllers and by observers in block 1, and it is not clear whether the increase in forward displacement based on experience is present only during observation and is not present during control (cf. Blättler et al., 2011; Blättler et al., 2010). Stork and Müsseler (2004) had participants visually track or fixate away from a moving target, and the vanishing point of the target was determined by the computer or by the participant's buttonpress. If participants tracked the target, forward displacement was smaller if the vanishing point was determined by participants rather than by the computer, whereas if participants did not track the target, forward displacement was not influenced by whether participants or the computer determined the vanishing point. Stork and Müsseler also measured spatial lag of the target by participants' eyes and eye motion after the target vanished, and they suggested that eye movements, coupled with visual persistence, produced forward displacement. However, and as was noted earlier, even if oculomotor behavior correlates with displacement for smooth motion targets, such behaviors cannot be primarily causal of representational momentum (for discussions, see Hubbard, 2005, 2006b, 2010).

Psychopathology

Given that representational momentum involves a bias in spatial localization, whether representational momentum occurs in patients who exhibit pathologies that influence spatial localization is of considerable interest. McGeorge et al. (2006) compared representational momentum for horizontal motion and vertical motion in patients with left spatial neglect, patients with right-hemisphere damage but no neglect, and control participants. Motion appeared smooth, and participants indicated the vanishing point by positioning a cursor. All groups exhibited significant representational momentum; there was no difference between leftward and rightward motion, but descending motion resulted in larger forward displacement than did ascending motion. Also, and as was noted earlier, forward displacement decreased with increases in distance traveled by targets in neglect patients and in patients with right-hemisphere damage, but not in control participants. McGeorge et al. suggested that forward displacement is impaired following right-hemisphere damage, because right-hemisphere damage influences endogenous attention and impairs ability to sustain attention on a target moving at a slower velocity or for a longer distance (cf. Amorim et al. 2000; White, Minor, Merrell, & Smith, 1993). However, McGeorge et al. reported that there was no correlation between the ability to sustain attention (as assessed by the digit symbol subtest of the WAIS–R) and the magnitude of representational momentum.

Lenggenhager et al. (2012) presented motion in the left, central, or right portions of the display (the left and right portions of the display were in the left and right visual fields, respectively, and the center portion of the display included portions of the left and right visual fields) to patients with left hemineglect following right-hemisphere damage, sex- and age-matched control participants, patients with right-hemisphere damage but no neglect, and one patient with left-hemisphere damage and right hemineglect. Motion in each visual field could be leftward, rightward, ascending, or descending. Motion appeared smooth, and participants indicated the vanishing point by touching the location in the display where the target vanished. Left hemineglect patients exhibited larger forward displacement than did control participants and other right-hemisphere patients, regardless of the direction of target motion. Furthermore, patients with left hemineglect, but not control participants or other right-hemisphere patients, exhibited larger forward displacement for targets moving toward the left. Consistent with this, the patient with right hemineglect exhibited larger displacement for targets moving toward the right. Lenggenhager et al. suggested that larger representational momentum for neglect patients might reflect nonlateralized components of attention (e.g. impairments in selective or sustained attention; cf. McGeorge et al., 2006) and that neglect patients exhibit over-extension in the representation of contralesional space.

De sá Teixeira, Pimenta, and Raposo (2013) presented schizophrenia patients and control participants with smoothly moving targets that varied in size and in velocity. Representational momentum increased with increases in size for both groups, and representational momentum increased with increases in velocity for control participants, but not for schizophrenia patients. These findings are notable for at least three reasons. First, representational momentum occurred in a population that usually exhibits dysfunction of pursuit eye movements. As was noted earlier, this is evidence against the hypothesis that pursuit eye movements are solely causal of representational momentum. Second, effects of implied mass on forward displacement are generally not reported within representational momentum literature (although effects of mass do influence displacement along the axis aligned with gravity; Hubbard, 1997). Third, velocity reflects kinematic information, and size (mass) reflects dynamic information. The relevant literature on perception and cognition typically focuses on how dynamic information can be extracted from kinematic information (e.g., Gilden, 1991; Shepard, 1994; P. A. White, 2012), thus implying that representation of dynamic information is reliant upon prior perception of kinematic information. Findings of de sá Teixeira, Pimenta, and Raposo (2013) that schizophrenia patients are sensitive to dynamic information but not kinematic information challenge the idea that dynamic information is necessarily inferred or derived from kinematic information.

Part II: Operational momentum

Whereas representational momentum typically involves movement in physical space, operational momentum involves movement in numeric space (e.g., along a mental number line). Just as there is forward displacement in physical space of the final location of a moving target, so too is there forward displacement in numeric space as a result of carrying out an arithmetic operation that implies movement along a mental number line (e.g., addition, subtraction). McCrink et al. (2007) and subsequent investigators demonstrated that participants generally overestimate the sum of an addition (involving rightward movement along a mental number line) and underestimate the difference of a subtraction (involving leftward movement along a mental number line); importantly, operational momentum involves impressions based on brief presentations of stimuli and is not based on explicit counting or calculation. Operational momentum appears to be a special case of representational momentum along a mental number line, and this is consistent with the abstract nature of momentum in representational momentum (cf. Finke et al., 1986); indeed, McCrink et al. and other investigators acknowledge the similarity of operational momentum and representational momentum. The literature on operational momentum is much smaller than the literature on representational momentum; effects of characteristics of the target, display, and observer have been reported, but effects of characteristics of the context have not been reported.

Target

As was the case for early investigations of representational momentum, characteristics of the target has been one of the most investigated areas in operational momentum literature. Findings considered here involve (1) distance, (2) size, (3) direction, and (4) symmetry.

Distance

Distance in operational momentum depends (at least in part) upon whether the mental number line is linear (e.g., Gallistel & Gelman, 2000) or compressed at higher ranges (e.g., perhaps logarithmic; Dehaene, 2003). Longo and Lourenco (2007) presented participants with lines or with pairs of Arabic numerals. Participants bisected a physical line by marking the perceived center of the line, and participants bisected their mental number line by estimating the number corresponding to the midpoint between two Arabic numerals. Significant leftward biases were observed in bisection of physical lines (cf. pseudoneglect, a leftward bias in line bisection exhibited by normal healthy adults; Jewell & McCourt, 2000) and in bisection of the mental number line. Bias on physical lines and bias on mental number lines were positively correlated, and this suggests that numerical representation may be spatial or involve spatial components (cf. SNARC effect; for a review, see Wood, Willmes, Nuerk, & Fischer, 2008). Error increased as the difference between numerals increased (cf. Pinhas & Fischer, 2008), and Longo and Lourenco suggested that higher values along the mental number line might be compressed. Also, a leftward bias is consistent with larger displacement for subtraction than for addition: If a leftward bias and operational momentum operate in the same direction (subtraction), they sum and displacement is larger, whereas if a leftward bias and operational momentum operate in opposite directions (addition), they partially cancel and displacement is smaller.

Size

"Size" can refer to the magnitude of individual operands in addition or subtraction or to the magnitude of a sum or difference. McCrink et al. (2007) presented a group of dots that entered the display from the left and moved behind a centrally located occluder. A second group of dots (1) entered from the right and moved behind the same occluder (addition) or (2) exited the right side of the occluder and moved off to the right (subtraction). The occluder then vanished and revealed some quantity of dots, and participants judged whether the quantity of revealed dots was correct or incorrect (given the number of dots that previously entered and/or exited the occluder). Knops, Viarouge, and Dehaene (2009) compared data from when two operands were the same (regardless of whether they were added or subtracted, and so outcomes were larger for addition than for subtraction) with data from when sums and differences were the same but operands differed (and so the outcomes for addition and subtraction were the same). McCrink et al. focused on single-digit numbers, but Longo and Lourenco (2007) and Lindemann and Tira (2011) reported operational momentum with multidigit numbers. In each of these studies, participants were biased toward smaller estimates in subtraction and toward larger estimates in addition. The size of the operands (in logarithmic coordinates) did not influence displacement, and this is consistent with the typical lack of a mass effect in representational momentum (e.g., Hubbard, 1997; but see de sá Teixeira et al., 2010).

Pinhas and Fischer (2008) presented symbolic information in the form of single digits or equations involving Arabic numerals (e.g., "3," "6–2"), and participants pointed to the location on a horizontal line that corresponded to the single digit or to the solution of an equation (the left and right endpoints of the line were labeled "0" and "10," respectively, but there were no other labels or markings). Pointing to the location on the line that corresponded to a single digit resulted in biases away from the center, and there was larger variability for larger digits. Pointing to the location on the line that corresponded to the solution of an equation revealed robust operational momentum that was stronger than the biases in single-digit pointing, and operational momentum was larger for subtraction than for addition. In order to obtain what the authors considered a "purer" measure of operational momentum uncontaminated by the size of the second operand, Pinhas and Fischer examined responses to equations in which the second operand was zero. Equations with zero as the second operand resulted in larger operational momentum than did equations with nonzero second operands. Pinhas and Fischer suggested that operational momentum reflected spatial activations related to the size of the operand, operator, and solution; the idea that displacement reflects activations from multiple aspects of a stimulus is consistent with the representational momentum literature (Hubbard, 1995c, 2005).

Direction

Operational momentum is usually larger for subtraction than for addition (e.g., Knops et al., 2009; McCrink et al., 2007; McCrink & Wynn, 2009). One possibility is that displacement along the number line reflects a combination of operational momentum with a bias to underestimate larger numerosities (cf. contributions of pseudoneglect to displacement along the mental number line; Longo & Lourenco, 2007): If this bias and operational momentum operate in the same direction (subtraction), they sum and displacement is larger, whereas if this bias and operational momentum operate in opposite directions (addition), they partially cancel and displacement is smaller. However, larger displacement for subtraction (leftward motion) does not seem consistent with similarity in displacement for rightward motion and leftward motion (Hubbard & Bharucha, 1988) or with larger displacement for rightward motion (Halpern & Kelly, 1993) reported for representational momentum. Although the mental number line is usually considered to be a horizontal line with smaller values on the left and larger values on the right, an effect of direction is also consistent with an alternative view of a vertical line with smaller numbers on the bottom and larger numbers on the top. With a vertical number line, subtraction and addition are analogous to descending and ascending motion, respectively (cf. Ito & Hatta, 2004), and so operational momentum might be influenced by representational gravity; paralleling studies of spatial localization, downward motion (subtraction) might result in larger forward displacement than would upward motion (addition).[4]

Symmetry

In studies of operational momentum, "symmetry" refers to whether the operands in an equation are the same (symmetrical) or different (asymmetrical). Charras, Molina, and Lupiáñez (2014; see also Charras, Brod, & Lupiáñez, 2012) presented participants with a reference number and a comparison stimulus that could be a single number (e.g., "48"), a repeated-operand addition (e.g., "24 + 24"), or a different-operand addition (e.g., "22 + 26"). In the latter two

[4] Because variables other than the implied momentum of a target influence displacement of spatial localization of that target, Hubbard (1995c, 2005) suggested that the term "representational momentum" should be applied to only the component of displacement that reflected implied momentum of the target and that the more general term "displacement" should be used to refer to the observed difference between the actual and judged vanishing points. Similarly, perhaps the term "operational momentum" should be applied to only the component of displacement along the number line that reflects arithmetic operations (and is separate from other components that might contribute to displacement along the mental number line—e.g., pseudoneglect), and the more general term "displacement" (or perhaps "numeric displacement") should be used to refer to the difference between the actual and judged sums and differences.

conditions, operational momentum predicts an overestimation for addition, and although different-operand addition resulted in overestimation, repeated-operand addition resulted in underestimation. This pattern held for larger (e.g., 48, 50, 52) and smaller (e.g., 8, 10, 12) sums. Somewhat surprisingly, if the operands were different from each other, the numerical distance between operands did not influence responses (cf. symbolic distance effect; Moyer & Bayer, 1976; Moyer & Landauer, 1967), and Charras et al. (2014) suggested that repeated-operand addition involves different processes than does different-operant addition. An important implication is that operational momentum is not determined solely by the operator (i.e., addition or subtraction) but is also influenced by characteristics of the operands. This might be loosely analogous to effects of target identity in representational momentum (e.g., an ascending target labeled "rocket" exhibits larger forward displacement than does an otherwise identical target labeled "steeple"; Reed & Vinson, 1996).

Display

Effects of only one characteristic of the display have been investigated in operational momentum literature, and that involves the surface form of the stimuli. Knops et al. (2009) presented nonsymbolic representations of quantities (i.e., clusters of dots) or symbolic representations of quantities (i.e., Arabic numerals). Participants were presented with a letter indicating which operation to carry out ("A" for addition, "S" for subtraction). They then viewed two consecutive displays, and each display contained clusters of dots or Arabic numerals. Participants then viewed a probe display containing seven potential solutions, and they indicated which potential solution was closest to the actual solution. Knops et al. (2009) reported that Arabic numerals resulted in operational momentum and that dot clusters appeared to result in operational momentum superimposed on a general tendency to underestimate the correct result (subtraction led to underestimation, but addition was not overestimated; also, inspection of their Figs. 2 and 7 shows that high-range sums were less likely to be overestimated than were low-range sums). McCrink et al. (2007) and Knops et al. (2009) noted that Freyd (1993) postulated representational momentum arises for targets based on continuous dimensions but not for targets based on discrete dimensions; Freyd's (1993) position suggests that representational momentum should not occur if targets involve discrete stimuli such as integers or Arabic numerals (cf. Crollen & Seron, 2012), but McCrink et al. and Knops et al. (2009) suggested that the underlying representation of quantities relied on analogue (continuous) numerical magnitudes rather than on discrete integers.

Observer

Effects of two characteristics of the observer have been investigated in operational momentum literature. Findings considered here involve (1) age and (2) attention.

Age

There have been two studies of operational momentum in nonadult human participants. McCrink and Wynn (2009) presented videos depicting addition or subtraction to 9-month-old infants. In both addition and subtraction, one group of objects descended from the top of the display and moved behind an occluder. In addition, a second group of objects then entered from the left of the display and moved behind the same occluder, and in subtraction, a smaller group of objects then exited from behind the same occluder. In both addition and subtraction, the occluder then moved offscreen to reveal a group of remaining objects, and the quantity of the remaining objects could be numerically correct, too large (consistent with operational momentum for addition), or too small (consistent with operational momentum for subtraction). Infants looked longer at outcomes that violated the hypothesis of operational momentum, and operational momentum appeared larger for subtraction than for addition. McCrink and Wynn suggested that the apparent existence of operational momentum in 9-month-old infants is (1) consistent with a hypothesis of developmental continuity in numerical representation and early development of spatial-numerical mappings and (2) inconsistent with a hypothesis that operational momentum arises from culture-specific schooling.

Knops et al. (2013) presented videos depicting addition or subtraction to 6- or 7-year-old children and to adult controls. A set of dots descended from the top of the display into a wooden box depicted at the bottom of the display; for addition, a second set of dots then descended from the top of the display into the same box, and for subtraction, a smaller group of dots then moved out of the box and vanished at the top of the screen. Participants then viewed a probe display containing six potential outcomes regarding the number of dots still in the box, and they indicated which potential outcome was correct. Adult controls exhibited a typical operational momentum effect. In a standard analysis, children did not exhibit operational momentum, but in a Bayesian analysis, children exhibited larger overestimation for subtraction than for addition (referred to as an *inverse OM effect*). Also, there was no relationship between reading fluency and operational momentum. Knops et al. (2013) suggested that the data were not consistent with explanations for operational momentum that were based on reading direction (e.g., the practice of reading English from left to right), compression of a mental number line (e.g., logarithmic representation of quantity), or heuristics (e.g., greater willingness to accept a larger quantity if adding

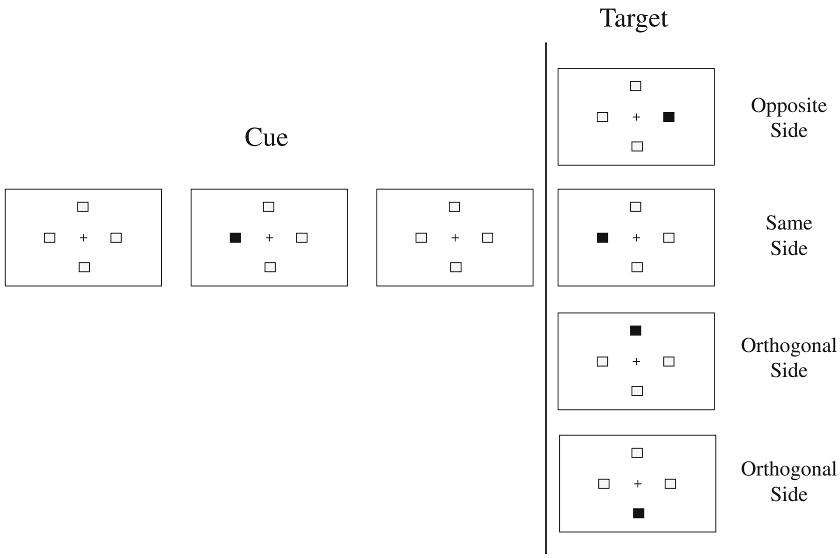

Fig. 2 An illustration of a typical methodology for an experiment assessing attentional momentum. The large rectangles are the outlines of the display, the small open squares indicate potential locations where the cue and the target could appear, and the cue and the target are indicated by black squares. The fixation point is indicated by the plus sign. After participants fixate, a cue appears at one location (in this example, the left), and then vanishes. Shortly thereafter, the target appears, and the location of the target relative to the location of the preceding cue varies across trials (each of the potential target locations is shown in the column on the right). The presence of attentional momentum would be indicated by a shorter response time to targets that appeared in the opposite-side location than to targets that appeared in one of the orthogonal-side locations

than if subtracting). The results were more consistent with an attention shift explanation, and this is consistent with the possibility of representational momentum along the mental number line.

Attention

Lindemann and Tira (2011) examined operational momentum for multidigit numbers. Participants were shown a single multidigit Arabic numeral (e.g. “34”) or an equation using Arabic numerals (e.g., “91 − 16”), and they rotated a knob that varied the quantity of dots in a display until that display contained a quantity of dots equal to the multidigit numeral or to the solution of the equation (cf. Crollen & Seron, 2012). The quantity of dots on the multidigit numerical task served as a baseline for the quantity of dots produced if the same number was the solution to an equation. There was a tendency to overproduce the quantity of dots, but this tendency was smaller for subtraction than for addition, and Lindemann and Tira interpreted this as consistent with operational momentum (since a smaller overproduction would be equivalent to a leftward shift along a mental number line). A similar pattern occurred if the second operand was a zero (cf. Pinhas & Fischer, 2008). Operational momentum did not occur if a solution required a “carry” or “borrow” operation, and it was suggested that such operations might engage more verbal processing and less analogue processing. Alternatively, such operations might simply require more attention, and this would be consistent with the decrease in representational momentum with increases in attention to the target (Hayes & Freyd, 2002; Hubbard et al., 2009). Lindemann and Tira suggested that their data were consistent with analogue representation of numeric information (consistent with Knops et al., 2009; McCrink et al., 2007; Pinhas & Fischer, 2008).

Crollen and Seron (2012) had participants reproduce the numerosity corresponding to an Arabic numeral by turning a knob to add or subtract from the quantity of dots in a display. In extensive displays, total surface area of the dots remained constant across increases or decreases in the quantity of dots (dot size decreased or increased with increases or decreases, respectively, in the quantity of dots), and in intensive displays, total surface area of the dots increased or decreased with increases or decreases, respectively, in the quantity of dots (dot size remained constant). In one condition, clockwise turning resulted in addition and counterclockwise turning resulted in subtraction, and in a second condition, clockwise turning resulted in subtraction and counterclockwise turning resulted in addition; the former was suggested to be consistent with the direction of operational momentum, and the later was suggested to be inconsistent with the direction of operational momentum. Participants overestimated numerosity regardless of direction or size of the turning movement (cf. Lindemann & Tira, 2011), and overestimation was larger for intensive stimuli when turning direction was inconsistent with operational momentum. Crollen and Seron suggested that overestimation was not due to an attentional bias that mimicked movement along a number line but was, instead, due to cognitive operations involved in mapping symbolic stimuli (Arabic numerals) to nonsymbolic stimuli (quantities of dots). However, it is not clear why such a mapping produced momentum-like effects in other experiments.

Part III: Attentional momentum

In a typical experiment on attentional momentum, participants view a central fixation point surrounded by several equidistant locations (see Fig. 2). One location is cued, and then a target is presented in the cued location or in an uncued location. If a target is presented in the uncued location that is opposite to the cued location, the time to detect that target is less than if a target is presented in some other uncued location, and this has been referred to as *attentional momentum* (e.g., Pratt et al., 1999). More broadly, attentional momentum suggests that the larger the change(s) in the direction of movement of attention to a target, the longer the response time to detect that target (i.e., it takes time and resources to overcome momentum related to the initial direction of movement of attention and to then shift attention to a new direction). If attention is moving from the cue back to a central fixation point when the target appears, attention is already moving in the general direction of the opposite uncued location, and no changes in the direction of movement of attention are needed. Also, it should be noted that if the target is presented in the cued location and stimulus onset asynchrony (SOA) between the cue and target is more than 200–300 ms, response time to detect the target is increased (Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughn, 1985), and this has been referred to as *inhibition of return* (for a review, see Klein, 2000).[5] The literature on attentional momentum is much smaller than the literature on representational momentum; effects of characteristics of the target, display, and observer have been reported, but effects of characteristics of the context have not been reported.

Target

Effects of four characteristics of the target have been investigated in attentional momentum literature. Findings considered here involve (1) direction, (2) distance, (3) eccentricity, and (4) color.

[5] Several studies that reported data relevant to attentional momentum were primarily concerned with inhibition of return (e.g., Samuel & Kat, 2003; Sumner, 2006). Within the literature, attentional momentum is often tied to inhibition of return, but attentional momentum and inhibition of return are in principle separate phenomena. As Snyder et al. (2009) pointed out "the OFE [opposite facilitation effect; i.e., attentional momentum] has little to do with IOR [inhibition of return]" (p. 1735). Despite the linkage in many studies of attentional momentum and inhibition of return, it is possible to consider shifts of attention using methodologies other than those also used to study inhibition of return, and this should be a priority for future studies of attentional momentum.

Direction

Effects of direction seem more absolute in representational momentum (upward vs. downward in physical space) and in operational momentum (rightward vs. leftward along the mental number line), but effects of direction were initially assumed to be more relative in attentional momentum, since the position of the cued location (and whether subsequent shifts of attention were rightward, leftward, upward, or downward) was not emphasized in initial studies of attentional momentum. However, reanalysis of Pratt et al.'s (1999) data by Snyder, Schmidt, and Kingstone (2001) found that attentional momentum occurred only if the cue was on the left (and momentum was toward the right). Consistent with this, Spalek and Hammad (2004) noted larger inhibition of return when movement of attention to the target would have been rightward and downward, and this was consistent with effects of direction in representational momentum (e.g., Halpern & Kelly, 1993; Hubbard, 1990). Such an effect of direction is consistent with the hypothesis that movement of attention across space may be similar to movement of an object across space. Such effects are also found when attentional momentum is triggered by symbolic stimuli such as words or arrows (e.g., Hommel, Pratt, Colzato, & Godijn, 2001; cf. Pratt & Hommel, 2003). However, it is not clear whether attentional momentum occurs only with rightward or downward movement of attention or whether previous methods were insufficient to detect a comparatively weaker attentional momentum for leftward or upward movement of attention.

Pratt et al. (1999) presented two potential peripheral cue and target locations (one to the left and one to the right of fixation), and another cue could appear near fixation, either on the same side as or on the opposite side from the earlier peripheral cue. If this additional cue appeared on the opposite side, movement from the peripheral cue to fixation to the additional cue was in the same direction, whereas if this additional cue appeared on the same side, movement from the peripheral cue to fixation to the additional cue involved a change in direction between peripheral cue to fixation and fixation to additional cue. In the latter case, the change in direction disrupted movement (and momentum) of attention toward the opposite side. Response times were shorter if the target appeared at the uncued location on opposite-side trials and at the cued condition on same-side trials. Pratt et al. then reversed presentation order of the fixation cue and the additional cue. With this change, opposite-side trials involved a reversal in the direction of movement of attention, whereas same-side trials involved a single direction of movement of attention. More inhibition occurred on same-side trials than on opposite-side trials. However, Snyder et al. (2001) reported a reanalysis of Pratt et al.'s data, as well as original data, that suggested that attentional momentum occurred in a minority of participants (whereas inhibition of return occurred in all participants, thus suggesting that inhibition of return and attentional momentum arose from separate mechanisms; see also Snyder, Schmidt, & Kingstone, 2009).

Jiang and Chun (2001) examined an asymmetrical effect in object substitution masking, in which a mask presented at a more peripheral location than the target resulted in decreased accuracy in identification of the target, relative to a mask presented at a more central location. One hypothesis to account for this asymmetry was attentional momentum; more specifically, orienting from a central fixation to a mask more peripheral than the target and then to the target would require reversing the direction of movement of attention, whereas orienting from a central fixation to a mask more central than the target and then to the target would not involve a change in the direction of movement of attention. Jiang and Chun tested an attentional momentum account by precuing the target or by making the target pop out from other elements in the display. The interaction between precuing and mask location was not significant, nor was the asymmetric pattern of substitution masking influenced by pop-out. Jiang and Chun interpreted these results as inconsistent with attentional momentum. However, Hirose and Osaka (2010) presented decoy stimulus masks along paths that deviated from the direction between fixation and the target, as well as masks more central or peripheral, and this allowed separation of the direction of movement of attention from the center–periphery relationships used in Jiang and Chun. Hirose and Osaka suggested that the asymmetric inhibition they observed could be implemented by attentional momentum.

Distance

The distance traveled by a target does not influence representational momentum (de sá Teixeira & Oliveira, 2011), and so it could be hypothesized that the distance traveled by attention should not influence attentional momentum. In the initial experiment in Pratt et al. (1999), potential cue locations and target locations were equidistant from a central fixation point. In a follow-up experiment, distances of potential cue locations and target locations from the fixation point varied. If a cue appeared at a location relatively near fixation, the distance between the cue and the opposite-side location was the same as the (straight-line) distance between the cue and each of the orthogonal-side locations. Participants were faster to detect targets in the opposite-side location than to detect targets in the orthogonal-side locations, and on the basis of similarity in distances, Pratt et al. ruled out spreading activation from the cue as a potential explanation for attentional momentum; however, they appeared to assume that spreading activation would be equal in all directions. It is possible that spreading activation toward the opposite-side location might be facilitated by movement between the cue and the fixation point. Hubbard (1995c, 2008; see also Müsseler, Stork, & Kerzel, 2002) suggested that representational momentum for a target reflected greater spreading activation in the anticipated direction of movement, and it is possible that attentional momentum might similarly reflect greater spreading activation in the direction of the initial movement of attention away from the cue.

Eccentricity

Spalek and Hammad (2004) presented eight potential cue and target locations in the form of an “X” (with the fixation point at the center of the “X” and two potential cue or target locations on each arm of the “X”). Cue eccentricity was significant, such that responses were faster if the cue was farther from fixation than if the cue was nearer to fixation. This effect is puzzling, since a constant velocity for the movement of attention might predict that responding should be faster if the cue was closer to fixation (and potentially closer to the target to be detected). One possibility is that the larger distance of the cue from fixation resulted in a relatively faster movement of attention that overcompensated for the increased distance. A faster velocity of movement of attention with larger distances appears consistent with Hubbard and Ruppel’s (2011) finding that ratings of relative velocity of movement in illusory line motion were higher with longer lines (although in control experiments, Hubbard & Ruppel did not find an effect of distance per se). Target eccentricity in Spalek and Hammad was significant, such that responses were slower if the target was farther from fixation than if the target was nearer to fixation. Effects of eccentricity are consistent with a general effect of distance, since a constant velocity of movement of attention would take more time to reach a more eccentric target (from a central fixation), although effects of distance per se were not reported. As would be expected, responses to the same (cued) side were slower than responses to the opposite (uncued) side.

Color

Sumner (2006) considered whether attentional momentum might be related to collicular or cortical mechanisms involved in inhibition of return. Sumner presented S cone stimuli (i.e., stimuli whose color change was detectable only by S cones), and since there are no projections from S cones to the superior colliculus, any inhibition of return or attentional momentum evoked by S cone stimuli must result from cortical projections. Color changes that were detectable by S cones but not by M and L cones were determined individually for each participant; cues were presented with S cone stimuli, and targets were presented in gray. Detection of targets in the cued location exhibited longer response times than did detection of targets in noncued locations, and the difference between the opposite-side location and the other noncued locations was significant with a one-tailed test. The pattern appeared to primarily reflect inhibition of the cued location, although there also appeared to be a small contribution of attentional momentum. In a follow-up experiment, cues were indicated by luminance changes detectable only by M and L cones. Results were the same as in the previous experiment, and this suggests the existence of two separable systems (a cortical system for endogenous orientation of attention, a collicular system involving saccades) for inhibition of responses. Sumner suggested that differences in detection latencies resulted primarily from inhibition of the cued location but that there might also have been a facilitatory effect due to attentional momentum.

Display

Effects of two characteristics of the display have been investigated in attentional momentum literature. Findings considered here involve (1) the cue and (2) SOA between the cue and the target.

Cue

Snyder et al. (2001) reasoned that if cue duration is an important determinant of when attention is shifted from the cued location, inhibition of return and attentional momentum should covary if cue duration is varied. They reported that a longer cue duration increased inhibition of return, but they did not observe attentional momentum. However, it seems likely that attentional momentum would be more related to the interstimulus interval during which movement of attention actually occurs (cf. effect of retention interval on representational momentum) or to the SOA of the cue and target than to the duration of a stationary cue prior to the movement of attention. Snyder et al. (2009) pointed out that in many experiments on inhibition of return or on attentional momentum, a fixation cue was presented after the initial cue regarding potential target location; this could have encouraged generation of a motion vector from the cued location that, if extended, would point to or reach the opposite-side location. If such a fixation cue is important for generation of attentional momentum, attentional momentum should occur if a fixation cue is presented and should not occur if a fixation cue is not presented. However, Snyder et al. (2009) reported that attentional momentum did not occur for approximately half of the targets regardless of whether a fixation cue was presented after the initial cue (whereas inhibition of return occurred for all targets, and so Snyder et al. rejected any connection between attentional momentum and inhibition of return).

SOA

Samuel and Kat (2003) examined the effect of SOA of the cue and target on detection of the target. Although their primary interest was to determine the duration of inhibition of return, they also examined differences in detection of targets at opposite-side locations or at orthogonal-side locations. They reported shorter response times for detection of targets at opposite-side locations than at orthogonal-side locations with a SOA of 600 ms (and data they replotted from Samuel & Weiner, 2001, suggested shorter response times at opposite-side locations than at orthogonal-side locations with SOAs of 400 and 500 ms), but not with an SOA of 1,200 ms. Samuel and Kat suggested that attentional momentum peaks quickly after cuing and is followed by a slower inhibitory process, and that whether attentional momentum or inhibition of response is observed might reflect the different time courses of attentional momentum and inhibition of return. The suggestion that attentional momentum peaks after a few hundred milliseconds and then decays is consistent with findings that representational momentum peaks after a few hundred milliseconds and then decays (for a review, see Hubbard, 2005). A similar time course for the effects of shifting the representation of a moving target forward in space (in studies of representational momentum) and for the effects of shifting attention across space (in studies of attentional momentum) suggests that representational momentum and attentional momentum involve similar or overlapping processes.

Observer

Effects of two characteristics of the observer have been investigated in attentional momentum literature. Findings considered here involve (1) attention and (2) eye movements.

Attention

Evidence consistent with a movement of attention similar to that in attentional momentum can be found in other literatures. In a study of representational momentum, Kerzel, Jordan, and Müsseler (2001) presented a leftward- or rightward-moving target and a subsequent probe slightly behind the final target location, at the final target location, or slightly beyond the final target location. Rather than judging whether the probe was at the same location as the final location of the target (as would occur if measuring representational momentum), participants judged whether a gap was at the top or bottom of the probe. With a retention interval of 90 ms between when the target vanished and when the probe appeared, participants were more accurate if probes were located in front of the final target location, rather than behind the final target location. This is consistent with a shift (and forward displacement) of attention in the direction of target motion. In a study of illusory line motion, Hamm and Klein (2002) presented four cue and target locations around a central fixation point. Each location contained an empty box; the cue was indicated by an increase in the brightness of one box, and the target was indicated by a decrease in the height of one box. After the cue was presented, a line appeared connecting two of the boxes. Responses to targets at a noncued location at the end of the line were faster than responses to targets at other noncued locations. Hamm and Klein suggested that attention follows motion. Given this, it is not surprising that if movement of a target exhibits momentum, movement of attention would exhibit an analogous momentum.

Eye movements

Machado and Rafal (2004) considered whether attentional momentum is based on saccade programming, since changing the direction of saccadic motion delays initiation of saccadic movement. More specifically, moving attention in a single consistent direction should be faster than moving attention an equivalent total distance in a sequence of different directions, and response times should increase as the number or magnitude of changes in eye movement direction increases. On endogenous trials, the location to be attended was cued by an arrow presented near fixation, and on exogenous trials, the location to be attended was cued by a white square in that location. Eye movements were monitored to ensure that (1) participants in endogenous trials saccaded to the white square and then moved their eyes back to the fixation point and (2) participants in exogenous trials did not move their eyes from the fixation point. Response times were longer to targets in the previously cued location, but response times to targets in the opposite location did not differ from response times to targets in other uncued locations. Neither the presence nor the absence of voluntary saccades was associated with attentional momentum, and this suggests that attentional momentum does not depend upon saccadic eye movements. Such a finding is consistent with occurrence of representational momentum for implied visual motion stimuli regardless of oculomotor behavior (Kerzel, 2003a).

Part IV: Comparisons and relationships

In Parts I, II, and III, variables that influence representational momentum, operational momentum, and attentional momentum were reviewed. Part IV summarizes similarities and differences in the effects of several variables on representational momentum, operational momentum, and attentional momentum; proposes a common underlying process or structure for displacement that involves spatial representation; and considers possible relationships of representational momentum, operational momentum, and attentional momentum.

Similarities and differences

Although some variables clearly influence one type of momentum-like effect more than another (e.g., velocity clearly influences representational momentum, but it is not clear what the analogue of velocity would be in operational momentum), other variables clearly influence multiple types of momentum-like effects. In the latter case, several variables have consistent influences on different momentum-like effects, and relatively few variables have apparently inconsistent influences on different momentum-like effects.

Representational momentum and operational momentum

Representational momentum and operational momentum occur with different surface forms (e.g., implied motion and smooth motion in representational momentum [Kerzel, 2003b]; digits and dot clusters in operational momentum [Knops et al., 2009]). The size of the target usually does not influence representational momentum per se (Hubbard, 1997; but see de sá Teixeira et al., 2010), and the size of operands in operational momentum does not influence operational momentum (Knops et al., 2009). Representational momentum is influenced by target identity (e.g., Reed & Vinson, 1996), and operational momentum is influenced by operand identity (e.g., Charras et al., 2014). Representational momentum (e.g., Kelly & Freyd, 1987) and operational momentum (e.g., McCrink et al., 2007) have been suggested to rely on analogue representation. Representational momentum (Hubbard, 1995c, 2005) and operational momentum (Pinhas & Fischer, 2008) reflect a combination of influences from multiple sources (e.g., larger displacement for subtraction reflects a combination of leftward bias and operational momentum, larger displacement for downward movement reflects a combination of downward bias [i.e., representational gravity] and representational momentum). Increases in attention to the target eliminate operational momentum (e.g., carrying or borrowing; Lindemann & Tira, 2011) and decrease but do not eliminate representational momentum (e.g., cuing final target location in representational momentum; Hubbard et al., 2009). Representational momentum (Perry et al., 2008) and operational momentum (McCrink & Wynn, 2009) appear to occur in very young children.

Discussions of operational momentum (e.g., Crollen & Seron, 2012; Knops et al., 2009; Longo & Lourenco, 2007; McCrink et al., 2007; Pinhas & Fischer, 2008) have acknowledged similarities of operational momentum and representational momentum, and McCrink and Wynn (2009) stated that “spatial extension of attention along the number line is one example of a broader class of anticipatory phenomena known as representational momentum” (p. 406). Operational momentum is consistent with the nature of representational momentum described by Finke et al. (1986), who stated: "Representational momentum can occur for extrapolations that have no simple analogue to the motions of physical objects. For example, implied changes in sounds, size, or color might give rise to a momentum effect if these changes can be extrapolated along some representational pathway" (p 176). Although Finke et al. did not address numerosity or discuss the mental number line as a representational pathway, it seems clear that operational momentum is consistent with their description of representational momentum. Thus, operational momentum might be a special case of representational momentum in which movement is not across physical space but is, instead, across the abstract space of the mental number line.[6] Also, just as the default forward displacement in representational momentum can be modulated by target-specific knowledge or expectations (e.g., changes in anticipated direction, target identity), so too can the default displacement of operational momentum be modulated by operand-specific or other information (e.g., leftward bias, symmetry).

Representational momentum and attentional momentum

Representational momentum (Freyd & Johnson, 1987) and attentional momentum (Samuel & Kat, 2003) peak after a few hundred milliseconds and then decline. Representational momentum (e.g., Hubbard, 1994; Reed & Vinson, 1996) and attentional momentum (e.g., Hommel et al., 2001) can be influenced by symbolic (verbal) information. Attentional momentum appears more fragile than representational momentum (e.g., attentional momentum occurs in a minority of participants; Snyder et al., 2001, 2009), and so momentum-like effects might be more robust if bound to a representation of a physical object than if bound to a (moving) fixation region or to the viewpoint of the self. Although Pratt et al. (1999) rejected a spreading activation account of attentional momentum, Hubbard (1995c, 2005, 2008) suggested that representational momentum reflected priming of the direction of target motion by enhanced spreading activation in the anticipated direction of motion, and such directional priming could potentially account for attentional momentum. Distance traveled by a target does not influence representational momentum in nonclinical populations (de sá Teixeira & Oliveira, 2011; McGeorge et al., 2006), but it is unclear whether distance of movement of attention influences attentional momentum. Relatedly, increases in target eccentricity lead to slower target detection (Spalek & Hammad, 2004) and to an increase and then decrease in representational momentum (Schmiedchen et al., 2013).

Spalek and Hammad (2004) suggested that movement of attention involves properties similar to physical momentum and that "once attention starts moving in a [specific] direction, it tends to continue moving in that direction until some force (effort) is directed against it" (p. 220). Such a notion is similar to descriptions of representational momentum; for example, Finke et al. (1986) stated that "mental extrapolations, like moving physical objects, cannot be instantly halted. Instead, they continue for some time after one begins to stop them . . . people can quickly stop the mental extrapolations only by applying an opposing, internal force" (pp. 176–177; cf. "compensation" in Joordens, Spalek, Razmy, & van Duijn, 2004). In studies of attentional momentum, differences in response times typically provide the most salient data (perhaps because of ceiling effects in accuracy), whereas in studies of representational momentum, differences in accuracy typically provide the most salient data (although response times were reported in early studies on representational momentum; e.g., Finke et al., 1986; Freyd & Finke, 1984). Emphases on accuracy or on response time might involve different aspects of a single "momentum" associated with shifts of a (target at the) represented or attended location. Interestingly, if data involve accuracy (and overshooting) of judged location, then the effects appear more likely to be termed "representational momentum," whereas if data involve time required for detection (and effects of changing the direction of an attentional shift), the effects appear more likely to be termed "attentional momentum."

Operational momentum and attentional momentum

There are fewer total similarities of operational momentum and attentional momentum than of operational momentum or attentional momentum with representational momentum, and this might reflect (1) the smaller literatures on operational momentum and attentional momentum or (2) operational momentum and attentional momentum resulting from separate (but possibly partially overlapping) subsets of representational momentum. Even so, a few similarities can be noted. Increases in distance between operands leads to more errors in operational momentum (Pinhas & Fischer, 2008), and increases in target eccentricity leads to slower responses in attentional momentum (Spalek & Hammad, 2004). Operational momentum can be eliminated by verbal information (e.g., in carrying or borrowing operations; Lindemann & Tira, 2011), and verbal information can influence attentional momentum (Hommel et al., 2001). Displacement is usually larger for leftward motion (subtraction) than for rightward motion in operational momentum (McCrink et al., 2007), but displacement is usually larger for rightward or downward

[6] There has been dispute over whether a mental number line is involved in numerical cognition or in operational momentum (e.g., Prather, 2012, suggested that tuning characteristics of neurons were sufficient to account for operational momentum and that appeal to a mental number line was unnecessary). However, the eventual resolution of this issue does not critically impact the discussion regarding the relationship of operational momentum and representational momentum, since displacement in operational momentum can be conceived of as involving any type of representation in which functional distance between quantities is preserved.

motion in attentional momentum (Spalek & Hammad, 2004). The latter difference might result from a compression of the right side of representational space (e.g., if the mental number line is logarithmically scaled) in operational momentum (or other numeric cognition) that does not occur in attentional momentum.

McCrink et al. (2007) proposed that operational momentum arises from an interaction between spatial and numerical systems that results from attention moving along a mental number line (cf. Crollen & Seron, 2012). This idea potentially unifies operational momentum and attentional momentum; indeed, operational momentum might reflect a special case of attentional momentum in which attention is not shifted across physical space but is shifted across the more abstract space of the mental number line. If operational momentum is a special case of attentional momentum and if, as was suggested earlier, attentional momentum and operational momentum are special cases of representational momentum, then the most general momentum-like effect would be representational momentum (involving displacement of a physical object across physical space), followed by attentional momentum (involving displacement of attention across physical space), followed by operational momentum (involving displacement of attention across an abstract numeric space). Regardless of the form of the relationships of representational momentum, operational momentum, and attentional momentum, the broadest similarity that emerges from consideration of these types of momentum-like effects is not the similarity of specific variables on more than one type of momentum-like effect but, rather, that all of these momentum-like effects involve displacement across some type of space.

Spatial representation

A spatial representation is a type of buffer that preserves information about spatial properties (e.g., distance between any given pair of locations) of a stimulus or set of stimuli as part of the functional architecture of that representation. An important aspect of such a representation is that properties and consequences of transformation in the representation parallel properties and consequences of transformations in physical space. This aspect of spatial representation is an important component in models of imagery such as Shepard's (1975, 1981) second-order isomorphism (e.g., longer mental rotation times for greater angular distances) and Kosslyn's (1980, 1994) visual buffer (e.g., longer scanning times for greater straight-line distances). Along these lines, Hubbard (2006a) discussed how the existence of representational momentum is predicted by Shepard's model, and Munger et al. (1999) found a correlation between the magnitude of representational momentum and the velocity of mental rotation. Even if a target representation is not initially spatial (e.g., symbolic Arabic numerals), spatial properties can influence subsequent processing if the initial representation of that target subsequently accesses or activates spatial (analogue) forms of representation. If a task involved transformation of quantity (e.g., addition, subtraction), use of a spatial representation (e.g., the mental number line) would result in properties of spatial transformation (momentum) influencing the response (i.e., operational momentum), and if location of a target in a spatial array was to be detected, properties of spatial transformation would influence the shift of attention across that representation (i.e., attentional momentum).

Involvement of a spatial representation in each of these momentum-like effects is consistent with the idea that displacement results from a single or small number of high-level processes (e.g., Hubbard, 2005, 2006a, 2006b), rather than from a multiplicity of distinct, separate, and modality-specific low-level processes (e.g., Kerzel, 2006). Also, given the usefulness of Cartesian analytic geometry and of spatial dimensions and coordinate systems in representing many types of information, it wouldn't be surprising if other types of information that initially appeared to be nonspatial might involve spatial information (e.g., hue, Shepard & Cooper, 1992; musical pitch, Krumhansl, 1990). Consistent with Finke et al. (1986), it could be predicted that momentum-like effects would be found whenever target information is transformed in a way that could be mapped onto a transformation across space (e.g., changes in auditory frequency are not obviously related to locations in physical space, but a mapping of auditory pitch onto a spatial up–down dimension results in representational momentum [e.g., Freyd, Kelly, & DeKay, 1990; Johnston & Jones, 2006] and representational gravity [e.g., Hubbard & Ruppel, 2013b] for auditory pitch). Additionally, other information regarding a target is often available to observers, and so information in spatial representation can be modulated by top-down or bottom-up stimulus- or situation-specific knowledge. Consistent with Hubbard (2006a), this suggests a two-stage process in which an initial default displacement that results from properties of spatial transformation can then be modified by top-down processes or other knowledge.

Possible typologies

Even if a common basis in spatial representation underlies representational momentum, operational momentum, and attention momentum, the relationships between these types of momentum-like effects are not entirely clear. One possibility is that operational momentum might be a special case of attentional momentum and attentional momentum might be a special case of representational momentum (see top panel of Fig. 3). This is a strongly hierarchical model. A second possibility is that operational momentum and attentional

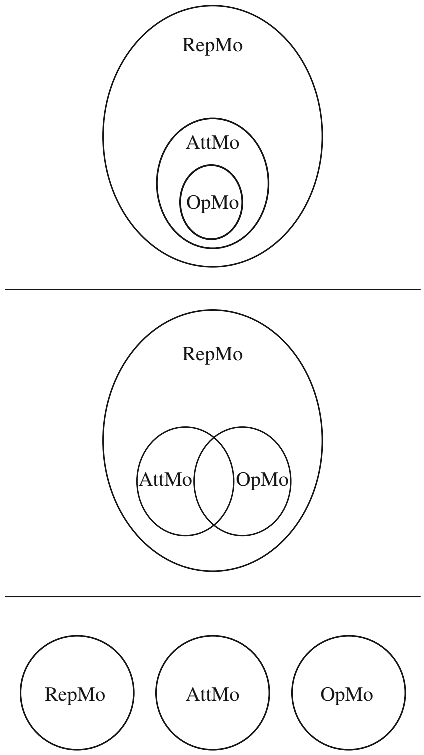

Fig. 3 An illustration of three potential relationships for representational momentum, operational momentum, and attentional momentum. In the top panel, operational momentum is a subset or special case of attentional momentum, and attentional momentum is a subset or special case of representational momentum. In the middle panel, operational momentum and attentional momentum are partially overlapping subsets or special cases of representational momentum. In the bottom panel, representational momentum, operational momentum, and attentional momentum are nonoverlapping processes at the same level

momentum might be special cases of representational momentum (see middle panel of Fig. 3). In this view, operational momentum and attentional momentum are each at the same level below the level of representational momentum, and they only partially overlap. A third possibility is that representational momentum, operational momentum, and attentional momentum might be separate and distinct processes at the same level (see bottom panel of Fig. 3). Other possibilities that involve representational momentum as a special case or subset of operational momentum or of attentional momentum can be tentatively rejected because of the narrower range of application of operational momentum and attentional momentum than of representational momentum.[7] The data and considerations of parsimony appear more consistent with the first or second possibilities, but the data cannot yet decide between these two possibilities. Regardless, representational momentum, operational momentum, and attentional momentum each appear to result from a momentum-like property of spatial representation.

If attentional momentum and operational momentum are special cases or subsets of representational momentum, attentional momentum and operational momentum should be consistent with (or at least not contradict) theories of representational momentum. Along these lines, operational momentum and attentional momentum appear more consistent with momentum metaphor and neointernalization theories of representational momentum than with low-level or belief-based theories (see Hubbard, 2010). As a further example, a case can be made for the adaptiveness of representational momentum and that representational momentum might have been selected for during our evolutionary history: Displacement consistent with momentum (or other invariant physical principles) could have aided in interactions with moving objects (e.g., predator or prey animals) by helping compensate for delays in perception due to neural processing time. More specifically, representational momentum displaces the represented position of a target to where that target would most likely be located in the immediate future, and so a participant's responses to the target would be more closely calibrated to where that target would be when a response would reach the target, rather than to where that target was initially sensed (for a discussion, see Hubbard, 2005). It is not as clear that operational momentum and attentional momentum are similarly adaptive, and so the latter momentum-like effects might just be unintended consequences of representational momentum that were not disadvantageous enough to be selected against (cf. Finke et al., 1986; Freyd, 1987).

Part V: Conclusions

Representational momentum, operational momentum, and attention momentum each reflect continuation of a current action or process, and these continuations involve a forward displacement in representation of that action or process that is attributed to a momentum-like effect. Variables that influence one of these momentum-like effects often have a similar influence on another momentum-like effect, although such comparisons are limited by the smaller number of variables investigated for operational momentum and attentional momentum than have been investigated for representational momentum. Relatively few variables have different influences on different momentum-like effects, and the differences that were found can be accounted for (e.g., compression of the right side of space in operational momentum but not in representational momentum). Findings of influences of specific variables on one type of momentum-like effect potentially provide

[7] A potential exception might be if representational momentum of an object actually involves momentum of attention (perhaps bound to an object), rather than momentum of the object itself. In this case, representational momentum would be a special case of attentional momentum in which an object is present. However, such a possibility does not seem consistent with the idea that increases in attention allocated to a target (e.g., selective attention rather than divided attention; Hayes & Freyd, 2002) or to the final position of a target (e.g., cuing of target location; Hubbard et al., 2009) lead to decreases in forward displacement of that target.

predictions regarding the influences of those variables on other momentum-like effects. Even so, the form of the relationships between representational momentum, operational momentum, and attentional momentum is not yet clear. It is likely, though, that operational momentum and attentional momentum are subsets or special cases of representational momentum in which displacement occurs in a specific type of space or involves movement of attention rather than movement of a target, respectively, and it is possible that operational momentum is a subset or special case of attentional momentum in which movement of attention occurs in a numeric space.

Representational momentum, operational momentum, and attentional momentum might reflect a more general phenomenon involving displacement in spatial representation. In each of these momentum-like effects, momentum (and resultant displacement) is across some type of space. For representational momentum and attentional momentum, this space usually corresponds to physical space (although examples of other types of space have been reported for representational momentum; e.g., auditory frequency space), and for operational momentum, this space corresponds to numeric space (e.g., the mental number line). Such a spatial representation would preserve information regarding spatial properties of objects and the environment, and properties and consequences of transformations within that representation would parallel properties and consequences of transformations of stimuli in physical space. Such a notion is consistent with models of visual imagery that posit analogue spatial representation, and so this approach potentially bridges internal representation in displacement with internal representation in imagery. Representational momentum suggests that the past action or state of a target or process can be used to anticipate the future action or state of that target or process, and operational momentum and attentional momentum might be unintended consequences of this more general predictive mechanism. In general, these momentum-like effects reflect dynamic transformations in representation, and similar shifts would occur whenever transformation of a target or execution of a process could be mapped onto a spatial representation or coordinate system.

Appendix

Table 1 Findings on representational momentum (RM) reviewed in Hubbard (1995c, 2005)

Variable	RM	Primary Sources
Velocity	RM is increased with increases in velocity	Freyd and Finke (1985), Hubbard (1990), Hubbard and Bharucha (1988)
	RM is decreased if a target is decelerating and increased if a target is accelerating	Finke et al. (1986)
Direction	Descending motion leads to larger RM than does ascending motion	Hubbard (1990, 1997), Hubbard and Bharucha (1988)
	Horizontal motion leads to larger RM than does vertical motion	Hubbard (1990), Hubbard and Bharucha (1988)
	No differences in RM between rightward motion and leftward motion	Hubbard (1990), Hubbard and Bharucha (1988), Cooper and Munger (1993)
	Rightward motion leads to larger RM than does leftward motion	Halpern and Kelly (1993)
	No differences in RM between clockwise motion and counterclockwise motion	Freyd and Finke (1984), Kelly and Freyd (1987)
	RM for clockwise motion is larger than for counterclockwise motion	Joordens et al. (2004)
	RM is larger for targets that rotate downward than for targets that rotate upward	Munger and Minchew (2002), Munger and Owens (2004)
	RM is larger with receding motion than with approaching motion	Hubbard (1996), Nagai et al. (2002)
	Rotation around an axis that corresponds to viewer or object coordinate system results in larger RM	Munger et al. (1999), Munger, Solberg, Horrocks, and Preston (1999)
Shape	RM is decreased if target shape varies inconsistently	Kelly and Freyd (1987)
	RM not influenced by implied drag resulting from shape	Cooper and Munger (1993)
	RM can be enhanced if an object moves in the direction in which it appears to point	Nagai and Yagi (2001)
	RM for shape occurs for consistent change in shape	Foster and Gravano (1982), Kelly and Freyd (1987)
Identity	RM is increased if target identity is consistent with motion	Reed and Vinson (1996), Vinson and Reed (2002)
Size	RM occurs for consistent changes in size	Hubbard (1996), Kelly and Freyd (1987), White et al. (1993)

Table 1 (continued)

Variable	RM	Primary Sources
Mass	Mass does not influence RM along the axis of motion	Cooper and Munger (1993), Hubbard (1997)
	Implied mass influences RM along the axis aligned with gravity	Hubbard (1995b, 1997, 1998)
	Smaller ascending targets exhibit less RM than do larger ascending targets	Kozhevnikov and Hegarty (2001)
Animacy	No difference in RM between drawings of animate and inanimate stimuli	Freyd and Pantzer (1995), Halpern and Kelly (1993)
Modality	RM occurs for changes in auditory pitch	Freyd et al. (1990), Hubbard (1995a), Kelly and Freyd (1987)
	RM occurs for moving sound sources	Getzmann, Lewald, and Guski (2004)
Surface form	RM is larger with continuous motion than with implied motion	Faust (1990)
	RM is larger with implied motion than with continuous motion	Kerzel (2003b)
	No difference between RM with implied motion or with continuous motion	Hubbard (1995a), Poljansek (2002)
	RM occurs with static stimuli that suggest motion	Freyd et al. (1988), Freyd and Pantzer (1995), Futterweit and Beilin (1994), Hubbard and Blessum (2001)
Latency to vanish	RM decreases with increases in latency between a button press to make the target vanish and when the target vanishes	Jordan et al. (2002)
Retention interval	RM increases during the first 200–300 ms	Freyd and Finke (1985), Freyd and Johnson (1987), Kerzel (2000)
	RM with 125- and 500-ms retention intervals do not differ	Halpern and Kelly (1993)
	RM decreases after approximately 500 ms	Freyd and Johnson (1987)
Response measure	RM is larger with cursor-positioning or reaching than with probe judgment	Kerzel (2003b), Kerzel and Gegenfurtner (2003)
	RM is larger with reaching when the hands are not visible than when the hands are visible or with cursor-positioning	Ashida (2004)
Error feedback	RM is impervious to error feedback	Finke and Freyd (1985)
Surrounding context	Orientation or movement of a surrounding or nearby stimulus influences RM	Gray and Thornton (2001), Hubbard (1993), Whitney and Cavanagh (2002)
	Motion of the self through a scene results in RM for the viewpoint	Munger et al. (2005), Thornton and Hayes (2004)
Landmarks	RM is increased if the target moves toward a stationary landmark and decreased if the target moves away from a stationary landmark	Hubbard and Ruppel (1999)
	A target moving along or parallel to a larger surface is displaced toward that surface	Hubbard (1995b, 1998)
	A stationary target is displaced toward a landmark	Hubbard and Ruppel (2000)
Expectations of future motion	If a reversal of target direction is expected, RM is backward (in the expected direction)	Hubbard (1994), Hubbard and Bharucha, (1988), Verfaillie and d'Ydewalle (1991)
	If a target is expected to stop as it approaches a barrier, RM is reduced or eliminated	Hubbard (1994), Hubbard and Motes (2005)
Attribution of the source of motion	RM is decreased if target motion is attributed to contact from another stimulus	Hubbard et al. (2001), Hubbard and Favretto (2003), Hubbard and Ruppel (2002)
Attention	RM is increased if attention is divided	Hayes and Freyd (2002), Joordens et al. (2004)
	RM is increased if a distractor is presented when the target vanishes	Munger and Owens (2004)
	RM is reduced or eliminated if a distractor is presented during the retention interval	Kerzel (2003a)
Eye movements	RM for smoothly moving targets is decreased if participants fixate away from (don't track) the target	Kerzel (2000, 2003b), Kerzel et al. (2001)
	RM for implied motion targets is not influenced by whether participants fixate away from the target	Kerzel (2003a)
	Oculomotor behavior does not influence RM with reaching when the hands are not visible but decreases when reaching and the hands were visible	Ashida (2004)
	Oculomotor behavior does not influence RM of a moving sound source	Getzmann (2005)
Action plans	RM is decreased if action plans are engaged (i.e., if participants trigger target disappearance)	Jordan et al. (2002), Jordan and Knoblich (2004)

Table 1 (continued)

Variable	RM	Primary Sources
Age	No difference in RM between third-grade, fifth-grade, and adult participants who viewed frozen-action photographs	Futterweit and Beilin (1994)
	First-grade participants exhibited larger RM than did fourth-grade or adult participants	Hubbard et al. (1999)
Psychopathology	A strong trend for patients with schizophrenia to exhibit larger RM than control participants	Jarrett, Phillips, Parker, and Senior (2002)
	Mentally challenged patients exhibit smaller RM than do control participants	Conners, Wyatt, and Dulaney (1998)
Physiology	RM is larger for stimuli in the left visual field	Halpern and Kelly (1993), White et al. (1993)
	Greater cortical activity in right parietal area when participants exhibit RM	Amorim et al. (2000)
	Presentation of frozen-action photographs actives motion area V5/MT	Kourtzi and Kanwisher (2000), Senior et al. (2000)
	TMS of V5/MT eliminates RM	Senior, Ward, and David (2002)
	Prefrontal and anterior cingulate may be activated in RM	Rao et al. (2004)

Note: The findings listed in Table 1 reflect knowledge of representational momentum at the time of Hubbard's (1995c, 2005) reviews. Many of these findings have been qualified or challenged by subsequent studies, and readers wishing for a complete understanding of the current knowledge regarding representational momentum should combine the information in Table 1 with the information in Part 1

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