Psychonomic Bulletin & Review (2022) 29:2015–2033
https://doi.org/10.3758/s13423-022-02130-z

THEORETICAL/REVIEW

The possibility of an impetus heuristic

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Accepted: 18 May 2022 / Published online: 15 June 2022

Abstract
Evidence consistent with a belief in impetus is drawn from studies of naïve physics, perception of causality, perception of force, and representational momentum, and the possibility of an impetus heuristic is discussed. An impetus heuristic suggests the motion path of an object that was previously constrained or influenced by an external source (e.g., object, force) appears to exhibit the same constraint or influence even after that constraint or influence is removed. Impetus is not a valid physical principle, but use of an impetus heuristic can in some circumstances provide approximately correct predictions regarding future object motion, and such predictions require less cognitive effort and resources than would predictions based upon objective physical principles. The relationship of an impetus heuristic to naïve impetus theory and to objective physical principles is discussed, and use of an impetus heuristic significantly challenges claims that causality or force can be visually perceived. Alternatives to an impetus heuristic are considered, and potential boundary conditions and falsification of the impetus notion are discussed. Overall, use of an impetus heuristic offers a parsimonious explanation for findings across a wide range of perceptual domains and could potentially be extended to more metaphorical types of motion.

Keywords Impetus · Naive physics · Perception of causality · Perception of force · Representational momentum · Heuristics

Heuristics are strategies, shortcuts, or "rules of thumb" that people often use when solving problems under conditions of uncertainty (Gigerenzer & Brighton, 2009). Since the idea of heuristics was popularized by Kahneman, Tversky, and colleagues (e.g., Kahneman et al., 1982) and by Gigerenzer and colleagues (e.g., Gigerenzer et al., 2011), there have been many different types of heuristics suggested. The discussion here focuses on the possibility of a heuristic based on the notion of impetus, and such a heuristic would likely be used when observers make judgments regarding the behavior of physical systems, and especially when observers make judgments regarding the potential or actual trajectory of a moving object within a physical system. Impetus is typically conceived of as a force that sustains object motion, and appeal to such a force is used in "common sense" explanations of why a moving object continues in motion or stops moving (Halloun & Hestenes, 1985). Evidence consistent with the use of an impetus heuristic is drawn from several different areas of empirical research, and the properties and characteristics attributed to impetus, as well as implications of an impetus heuristic, the relationship of an impetus heuristic to Newtonian physics, alternatives to an impetus notion, and potentially broader applications of an impetus notion, are discussed. The possibility that a belief based on impetus can function as an implicit physical theory, and whether such a function is consistent with the use of impetus as a heuristic, is also considered.

Impetus is a notion with a long history, and versions of the impetus notion were discussed by Aristotle and by pre-Newtonian medieval thinkers (for overview, see Halloun & Hestenes, 1985; Kozhevnikov & Hegarty, 2001; McCloskey, 1983; White, 2009b). Impetus has generally been considered to be a force acquired by an object whose motion was caused or influenced by an external source, and so an object that began moving without being acted upon (i.e., that exhibited autonomous or self-generated motion) would not exhibit impetus. Thus, possession of impetus is potentially limited to those objects whose motion is caused or constrained by an interaction with another object (e.g., being collided with or contained within). Because impetus involves a force that

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is believed to be imparted from another object, it does not arise from self-generation, and it is believed to begin to dissipate immediately after being imparted to an object; this dissipation results in object motion eventually stopping or other influences on object motion being exhibited. Although some researchers have suggested that a belief in impetus involves an implicit physical theory (e.g., McCloskey, 1983), other researchers have suggested that a belief in impetus can be regarded as a heuristic involved in judgments regarding moving targets (e.g., Kozhevnikov & Hegarty, 2001). As impetus does not correspond to a valid (Newtonian) physical principle, the use of an impetus heuristic would significantly challenge claims that individuals can visually perceive causality and force and would have important implications for claims that individuals can accurately represent the behavior of objects in dynamic physical systems.

The first to suggest that beliefs regarding impetus might be used as a heuristic were Kozhevnikov and Hegarty (2001). The consideration here develops the notion of an impetus heuristic beyond what Kozhevnikov and Hegarty originally proposed by moving beyond naïve physics to consider the notion of impetus in the perception of causality, the perception of force, and the representation of object location more broadly; providing an extended discussion of how an impetus heuristic is useful and why such a heuristic might have evolved; elaborating the differences between naïve impetus theory and an impetus heuristic (e.g., whether contact from another object is required, whether impetus can be added as well as subtracted during motion); discussing how characteristics of a potential impetus heuristic are similar to characteristics of other heuristics; discussing the relationship of an impetus heuristic to theories and models that challenge the notion of a belief in impetus (e.g., property transmission, action-at-a-distance, kinematics specifies dynamics, noisy Newton); providing a discussion of potential boundary conditions for application of an impetus heuristic (e.g., whether motion of the object is autonomous or self-generated, whether object properties are consistent with properties attributed to impetus); considerations for potential falsification of an impetus heuristic; consideration of when representational momentum might or might not reflect belief in impetus; and suggesting an impetus heuristic might be applied to stimuli in domains in which change could be considered as movement or a motion path within a metaphorical coordinate space.

Part I: Types of empirical evidence

Evidence suggestive of a belief in impetus and the use of an impetus heuristic in four different areas of empirical research are considered, and these areas include studies of naïve physics, perception of causality, perception of force, and representational momentum. Full reviews of these areas are beyond the scope of this article, but findings in each of these areas that are relevant to an impetus notion are considered. Potential relationships of these different areas to each other are also considered, and the notion of impetus is seen to offer a parsimonious explanation for findings across these different areas.

Naïve physics

How individuals who have not received formal instruction in physics understand and conceptualize the behavior of inanimate objects and other physical systems in the world is referred to as *naïve physics* (e.g., McCloskey, 1983; also referred to as *intuitive physics*, e.g., Vicovaro, 2018, or *folk physics*, e.g., di Sessa, 1996). Naïve physics has generally been studied by interviewing participants regarding their beliefs about physical systems and by laboratory tasks in which experimental participants make judgments regarding a potential or observed trajectory of a moving object. Several studies involving interviews have provided evidence consistent with an impetus heuristic. Clement (1982) reported that Introductory Physics students often believed that motion of an object was due to a force that was greater than any opposing force and that changes in the velocity of that object were due to this force "dying out" or "building up." Di Sessa (1993) interviewed physics students and documented beliefs that heavy or large objects resist motion and that all motion "dies away." Halloun and Hestenes (1985) interviewed college students and documented beliefs that impetus is necessary to sustain motion, exists independently of external agents or objects, can be imparted or transmitted from one object to another object, and is proportional to object mass and velocity. Cooke and Breedin (1994a), Donley and Ashcraft (1992), and McCloskey (1983) administered interviews or questionnaires and found evidence consistent with a belief in impetus and that such beliefs were more common in those who had not received formal instruction in physics.

Many laboratory studies of naïve physics have provided evidence consistent with an impetus heuristic, and examples of these are shown in Fig. 1. McCloskey et al. (1980; McCloskey & Kohl, 1983) found that many experimental participants failed to correctly predict the path that would be followed by a ball shot out of the end of a curved or spiral-shaped tube or failed to correctly predict the path that would be taken by a ball being whirled on a string when the string was cut. Rather, those experimental participants appeared to appeal to a curvilinear impetus notion that suggested that an object moving along a curved path would continue along that path (or along a gradually straightening path) even after the constraints that led to the original curved path were removed. Participants who had not taken a high school physics course made the most errors, and participants

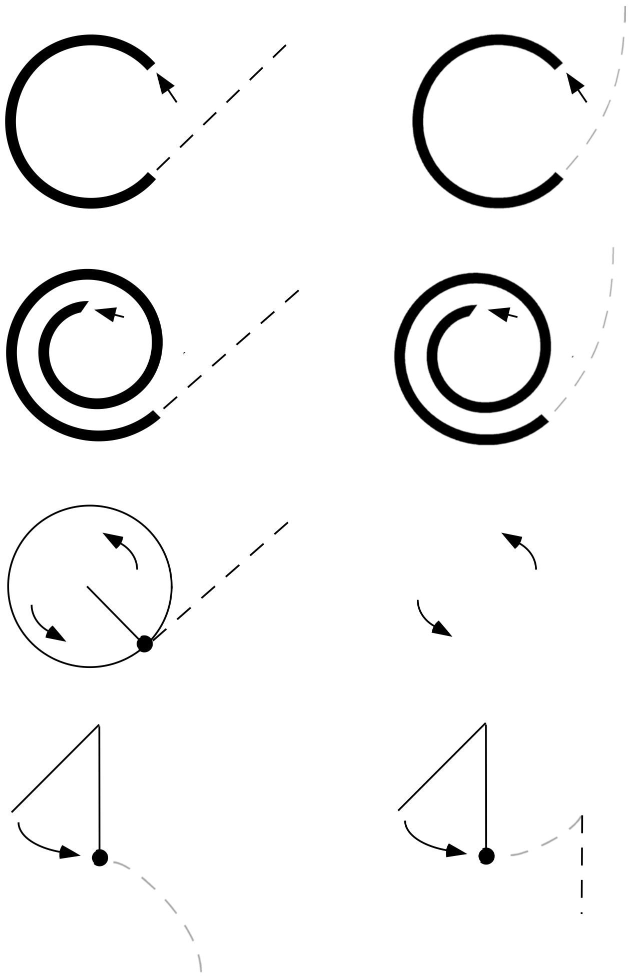

Fig. 1 Naïve physics tasks that can result in an impetus response. *Note*. The first row shows a curved tube, the second row shows a spiral tube, the third row shows a ball on a string being whirled in a circle, and the fourth row shows a swinging pendulum (rows 1–3 show stimuli oriented in the horizontal plane, and row 4 shows a stimulus oriented in the vertical plane). Possible predictions are shown by the dashed lines; physically correct responses are shown in the left column and responses consistent with impetus are shown in the right column. In the first two rows, a ball inserted in one end of the tube (indicated by the arrow) and shot out of the other end of the tube. In the third row, a ball is being whirled in a counterclockwise direction, and the string is cut. In the fourth row, a pendulum is swinging from the left to the right, and the string holding the pendulum is cut. Adapted from McCloskey (1983)

who had taken a college physics course made the fewest errors. Analogous results were found when experimental participants were shown drawings of a swinging pendulum and asked to indicate the direction the pendulum bob would move if the string were cut at various locations within its arc of motion (Caramazza et al., 1981). Responses suggested that many participants believed motion of the swinging pendulum imparted an impetus that made the pendulum bob continue on its previous (curved) path, and then after impetus along that path was dissipated, the pendulum bob would fall straight down. In general, between 30% and 50% of participants in these types of laboratory studies exhibit responses consistent with an impetus belief (White, 2012c).

Information regarding impetus might be more likely to be used if less information was available (e.g., if experimental participants predicted future motion based on a static display rather than judged the correctness or naturalness of an observed motion). Indeed, when presented with an animated version of a target being ejected from a curved tube (which provided more information than did a static drawing), participants were less likely to prefer a curvilinear path consistent with impetus (Kaiser et al., 1985). Relatedly, experience with video games that present realistic object motion trajectories can enhance participants' ability to predict object motion trajectories when shown static stimuli, although such improvements are relatively small (Masson et al., 2011). However, animation does not aid performance when there is more than one dimension of dynamic relevance (Kaiser et al., 1992; see also Proffitt & Gilden, 1989). The limitation to one dimension suggests a limitation of processing capacity, and as many real-world stimuli involve more than one dimension of dynamically relevant information (e.g., mass distribution, center of mass, etc.), the need for a heuristic approach is underscored; indeed, one characteristic of heuristics is that they are "frugal," that is, heuristics use only some of the potentially available information. Thus, the notion that impetus might be used as a heuristic in judgments or predictions of object motion is consistent with claims that judgments of dynamic physical systems are based on heuristics (e.g., Gilden & Proffitt, 1989; Proffitt et al., 1990; Proffitt & Gilden, 1989).

Based upon interviews with experimental participants and behavioral data from laboratory experiments, McCloskey (1983) proposed that results of many experiments on naïve physics could be accounted for if experimental participants possessed a belief similar to the impetus notion. McCloskey referred to this as *naïve impetus theory*, and there are two key parts of this theory: First, when a moving object contacts a stationary target, that moving object imparts impetus to the stationary target, and if the magnitude of impetus is sufficient, the previously stationary target will begin moving. Second, if the previously stationary target begins moving, then any impetus that was imparted is dissipated by subsequent target motion. Once impetus drops below the level needed to sustain motion, target motion stops (or can then be influenced by other factors operating on the target, e.g., a projectile continues in its current path until its impetus has dissipated, at which time it falls straight downward due to gravity, e.g., Caramazza et al., 1981). One form of impetus addressed by naïve impetus theory is curvilinear impetus, in which an object previously constrained to move in a curved path would continue to move in a curved path even after the constraints were removed

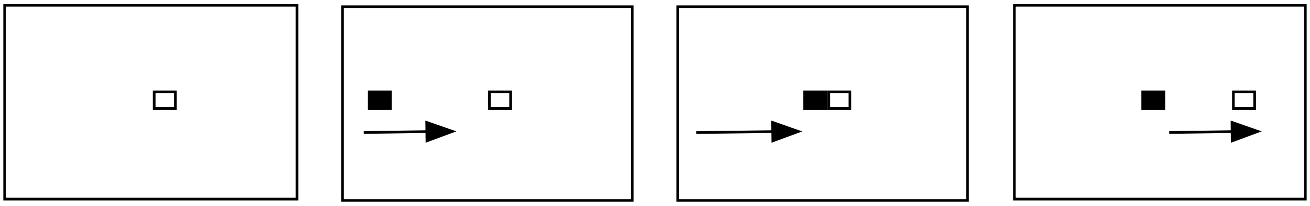

Fig. 2 The launching effect. *Note*. Time moves from left to right. A stationary target (white box) is shown near the center of the display (frame 1). A launcher (black box) enters the display and moves toward the target (frame 2). The launcher contacts the target and becomes stationary (frame 3), and the target then moves away from the launcher (frame 4). Adapted from Hubbard and Ruppel (2002)

(Caramazza et al., 1981; McCloskey et al., 1980; McCloskey & Kohl, 1983). More broadly, any continuing influence of a previously removed constraint on target motion is potentially consistent with impetus. A second form of impetus involving linear motion has also been addressed, as lighter objects are believed to ascend faster than do heavier objects (Kozhevnikov & Hegarty, 2001).

Not all findings in naïve physics literature appear consistent with naive impetus theory. As noted earlier, experimental participants are less likely to accept a path consistent with curvilinear impetus when viewing an animation of a ball exiting a spiral tube than to predict such a future path for a ball that would exit a spiral tube (Kaiser et al., 1985). Also, experimental participants are less likely to predict a path consistent with curvilinear impetus for water that exited a curved hose (Kaiser et al., 1986) than for a ball that exited a curved tube (McCloskey et al., 1980). Other findings include beliefs that a thrown ball continues to accelerate after leaving the hand (Hecht & Bertamini, 2000), that velocity of a ball rolling down an incline is a function of the local slope rather than the net vertical drop since motion began (Rohrer, 2002, 2003), and that an object dropped from a horizontally moving object will fall in a straight line (McCloskey et al., 1983).[1] As there are numerous other findings that are consistent with an impetus notion, such inconsistences might reveal important boundary conditions of the impetus notion rather than provide a disconfirmation of the general impetus notion. In the case of impetus, such boundary conditions would reflect stimulus properties inconsistent with properties attributed to impetus (e.g., if stimulus motion appeared self-generated) and in which other heuristics (e.g., objects that are faster or ricochet farther have less mass; Gilden & Proffitt, 1989) are utilized. Interestingly, some of the examples above are more consistent with the view of Kozhevnikov and Hegarty (2001) that impetus can be acquired from a force (gravity) that acts on an object and without contact from another physical object.

Perception of causality

Although impetus has been widely discussed within the literature on naïve physics, impetus has generally not been discussed within the literature on perception of causality (for exceptions, see Hubbard, 2013c; Sanborn et al., 2013; White, 2012c), despite studies on naïve physics and studies on perception of causality each examining judgments of observers regarding the motion of objects in physical systems. The prototypical stimulus used in investigation of perception of causality is the launching effect, which was first documented by Michotte (1946/1963; for review, see Hubbard, 2013b, 2013c) and is shown in Fig. 2: A moving object contacts a stationary object, and at the moment of contact, the previously moving object (henceforth referred to as a *launcher*) stops moving and the previously stationary object (henceforth referred to as a *target*) begins moving at a similar or slower velocity and in a direction similar to that of the previous motion of the launcher. If the parameters of target motion are within a narrow range of values (e.g., latency between when the launcher stops moving and when the target begins moving is less than 100 ms, subsequent target velocity is less than or equal to previous launcher velocity, the direction of subsequent target motion is similar to the direction of previous launcher motion), then observers often spontaneously claim to perceive (or have an impression) that the launcher caused the target to move; if the parameters of

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[1] In some examples in which impetus is not attributed to an object, object motion is not autonomous or self-generated, and so it might not initially be clear why impetus would not be attributed and why such examples would not provide disconfirmation of the impetus hypothesis. For example, motion of a dropped object is not autonomous or self-generated, and yet naïve impetus theory suggests that impetus is not attributed to a dropped object. In the case of a dropped object, impetus is not attributed to that object because at the moment an object is dropped, it loses contact with another object rather than being contacted by another object, and there is no force imparted to that object by the loss of contact. Thus, a dropped object does not meet the characteristics that naïve impetus theory suggests are necessary for impetus to be attributed (a contact at which impetus is imparted), and so the lack of a response consistent with impetus does not falsify the general impetus hypothesis. Similarly, no impetus-like force from contact with another object is imparted to an object rolling down an incline, and the continued acceleration of a thrown ball after leaving the hand might involve a brief forward extrapolation of the acceleration of the ball after the ball is released.

target motion are outside of that narrow range of values, then a perception that the launcher caused the target to move is less likely. Based on these differences, Michotte (1946/1963) claimed the launching effect demonstrated that observers can actually perceive causality in some stimuli.

The idea that there might be a force such as impetus that is imparted from the launcher to the target in the launching effect was tested in several studies that presented a spatial gap between the final location of the launcher and the initial location of the target. Ratings of causality were highest when the launcher contacted the target; if there was a spatial gap between the final location of the launcher and the initial location of the target, then ratings that the launcher caused the motion of the target were decreased (Michotte, 1946/1963; Yela, 1952). This is consistent with an impetus notion, as without contact, it is not clear how the launcher could directly impart impetus to the target.[2] An exception to the effect of a spatial gap between the final location of the launcher and the initial location of the target occurs when the spatial gap is bridged by an intermediary object. Michotte (1951/1991) referred to such an intermediary as a *tool*, and he suggested such an intermediary was perceived to convey the influence of the launcher to the target and referred to this as a *tool effect*. In other words, the cause of target motion was attributed to the launcher and not to the intermediary; rather than being perceived as two consecutive launching effects (i.e., the launcher launching the intermediary and the intermediary launching the target), the tool effect was perceived as a single effect in which the launcher launched the target via the intermediary. Relatedly, introduction of a temporal gap between when the launcher contacted the target and when the target began moving led to a decrease in ratings of causality (Michotte, 1946/1963), and this is also consistent with an impetus heuristic, as impetus would be imparted immediately upon contact.

If a stationary object bridged the spatial gap between the final location of the launcher and the initial location of the target, then ratings that the launcher caused motion of the target were reduced but were higher than when such a stationary object bridged only a part of the gap or the gap was empty (White, 2011a; Young & Falmier, 2008). When the gap was filled with smaller white stationary objects that successively changed to black and the direction of color change was from the gap object nearest the black launcher to the gap object nearest the white target, ratings were higher than when there was no color change or when the direction of color change was from the target to the launcher (White, 2015). Hubbard and Ruppel (2018) found that when the amount of color change suggested that more of the influence of the launcher was preserved across the gap (i.e., all gap objects turned from white to black), ratings of causality were higher than when color changes suggested a dissipation of the influence of the launcher across the gap (i.e., the initial gap object turned black, and subsequent gap objects turned successively lighter shades of gray). More generally, a sequential change in object properties in the direction of a causal influence can give rise to a visual impression of a generative transmission (White, 2015). Consistent with this, Vicovaro et al. (2020) suggested transmission of impetus in collisions can be viewed as an example of the property transmission hypothesis proposed by White (2009b, 2010), which suggests that causal objects impose their own properties on effect objects (e.g., impetus initially attributed to the launcher is perceived to be transmitted [imparted] to the target).

Effects of the relative velocities of the launcher and the target are also consistent with impetus. For a launching effect to occur, the subsequent velocity of the target should be less than or equal to the previous velocity of the launcher (Michotte, 1946/1963). The limitation of target velocity in a launching effect to less than or equal to the previous launcher velocity is consistent with an impetus heuristic. If faster launcher velocities are associated with imparting more impetus to the target, then a subsequent target velocity that is faster than the previous launcher velocity would suggest a launcher imparted more impetus than it possessed. However, a launcher imparting more of some quality than it possesses (or is believed to possess) is not possible, and so a launching effect is not perceived. Curiously, the judgment of post-collision velocity of the target is biased toward the average pre-collision velocity of the launcher, rather than toward the velocity of the launcher at the time of contact (Vicovaro, 2018); it is not clear how this is consistent with an impetus account or a Newtonian account, as such accounts would presumably focus on the velocity of the launcher at the time of contact. Furthermore, effects of the ratio of launcher velocity and target velocity are influenced by contextual factors (Schlottmann & Anderson, 1993), which is also consistent with use of a heuristic. As perception of causality involves expectations regarding when the target will move and not just whether the target will move (e.g., Young et al., 2005), launcher velocity would also be especially critical if the influence of the launcher is expected to cross a gap (e.g.,

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[2] Although the launching effect is considerably weakened with spatial gaps between the final location of the launcher and the initial location of the target, a launching effect can still be obtained when there is a spatial gap, especially when target velocity is high (Yela, 1952). It could be speculated that causality is like a wave or a field; just as a magnetic field can operate across a spatial gap between a magnet and a piece of iron, so too might causality operate across a spatial gap between a launcher and a target. Thus, just as the strength of a magnetic field is weakened by increases in distance and are stronger with contact, so too are effects of causality weakened by increases in distance and are stronger with contact. Analogously, impetus might also be viewed as a wave or field, and so capable of operating across a spatial gap. Even so, just as a spatial gap can decrease the strength or likelihood of a launching effect, so too might a spatial gap decrease the strength or likelihood of a response consistent with impetus.

via a tool or gap objects), as different velocities would presumably require different durations to cross a given gap size.

According to Newtonian physics, in a collision between a launcher and a target, the launcher exerts a force on the target, and the target exerts an equal force on the launcher (as after all, in the launching effect the launcher typically stops upon contact with the target). However, in describing their perceptions, observers overwhelmingly focus on effects of the launcher on the target (White, 2007), and this has been referred to as a *causal asymmetry* (White, 2006). White initially suggested that causal power in an interaction is typically attributed to the object that was moving first or that was changed the least by contact (e.g., White, 2006, 2007), but later suggested that other objects might be perceived as causal (e.g., White, 2012d). Indeed, Hubbard and Ruppel (2013) found that if a launcher shattered upon impact with a target that remained stationary, the target rather than the launcher was perceived as more causal. Similarly, if a launcher stopped before contacting a target that remained stationary, causal ratings of the launcher and of the target were highly similar and decreased with increases in the spatial gap between the final location of the launcher and the location of the target (Hubbard & Ruppel, 2017). Importantly, causal asymmetry is consistent with the notion that observers are not actually perceiving causality, and this possibility is consistent with the use of a heuristic based on impetus. Even so, as impetus is usually considered as causing or perpetuating an object's motion, it does not seem reasonable to attribute impetus to a target that remains stationary after contact and is perceived to be the cause of the shattering of a launcher, unless whatever impetus is imparted is less than the level needed to overcome resistance and initiate motion of that target.

The focus in this section has been on the potential role of impetus in the launching effect and in the tool effect, and the potential role of impetus in the entraining effect is discussed below (see Hubbard, 2013c, for discussion of impetus in other examples of perception of causality). Also, just as not all examples of naïve physics involve or are consistent with an impetus notion, not all examples of perception of causality involve or are consistent with an impetus notion. Examples of perception of causality in which an impetus notion would not apply include the triggering effect (in which subsequent target motion is faster than previous launcher motion and perceived as autonomous or self-generated; Michotte, 1946/1963), pulling effect (when an initially moving object appears to continually pull [tow] a previously stationary set of objects; White & Milne, 1997), and braking (a change in velocity when a target moves over a different background; Levelt, 1962). As noted earlier, just because a heuristic is not relevant to every exemplar within its potential domain is not evidence against the existence of such a heuristic, but instead suggests potential boundary conditions of that heuristic. In the case of perception of causality, an impetus notion appears more consistent with cases in which motion of a previously stationary object is attributed to a brief contact from another object and is not perceived to be autonomous or self-generated. Also, as a contact between objects would likely involve force, attribution of impetus in the perception of causality might be related to perception of force, and so implications of findings regarding perception of force for an impetus heuristic are relevant.

Perception of force

From at least the medieval period, impetus has been characterized as an "acquired force" (see Halloun & Hestenes, 1985; McCloskey, 1983), and this raises the question of how force is related to causality. Indeed, descriptions of causality often appear to involve application of force by one stimulus on another stimulus (cf. Talmy, 1988; Wolff & Barbey, 2015). Consistent with this, White's (2012b) theory that visual perception of causality is based upon previous haptic experiences of applying force to objects suggests a close link between causality and force (see also Hubbard, 2012; White, 2012a). Given this, the possible relationship between the perception of force and attribution of impetus is important. White (2007) presented launching effect stimuli and found that ratings of the force of the launcher on the target were similar to previous findings regarding ratings of the causality of the launcher for movement of the target. Also, just as there is an asymmetry between whether the launcher is perceived to be the cause of the target's initiation of motion and the target is perceived to be the cause of the launcher's cessation of motion, there is an asymmetry in that the launcher is perceived to impart more force to the target than the target is perceived to impart to the launcher, and this is referred to as a *force asymmetry* (White, 2007, 2011b). Both force asymmetry and causal asymmetry are consistent with Michotte's (1946/1963, p. 217) hypothesis of ampliation that suggests "the dominant movement, that of the active object, appearing to extend itself on to the passive object," as force asymmetry and causal asymmetry, as well as ampliation, stress a single direction of influence from an initially moving (active) object to an initially stationary (passive) object (cf. McCloskey, 1983; Wolff, 2007).

Within Newtonian physics, the terms "force" and "resistance" refer to the same characteristic of an object (cf. resistive force). However, White (2009a) suggested that "force" is often viewed as an active quality (e.g., of a moving stimulus) and "resistance" is often viewed as an inactive or passive quality (e.g., of a stationary stimulus). Consistent with this, ratings of force and ratings of resistance for the same stimulus can be different (e.g., White, 2011b). Also, ratings of the causality and ratings of the force of a stationary target that was perceived to have stopped the previous motion of a launcher decrease with increases in the distance between the final location of the launcher and the location of the target, but ratings of the resistance of the stationary target in stopping motion of the launcher increase with increases in the distance between the final location of the launcher and the location of the target (Hubbard & Ruppel, 2017), and this was referred to as a *force-resistance asymmetry*. Such an asymmetry might reflect a judgment that more total resistance is needed to stop a launcher that is farther from a target and the possibility that an effect from the target on the launcher is more likely or more forceful if the launcher is closer to the target. Ratings of force are generally similar to ratings of causality (Hubbard & Ruppel, 2013, 2017, 2018; White, 2007; but see White, 2011a, 2014), and this is consistent with the possibility that a belief in impetus contributes to perception of force and to perception of causality. Even so, it is not clear how a belief in impetus might contribute to perception of resistance, as resistance is typically attributed to a stationary target (or surface) rather than to a moving object, and a stationary target (or surface) would not possess impetus.

Several studies have examined effects of object velocity on ratings of force. White (2007, 2009a) reported that ratings of the force of the launcher on the target were higher if the velocity of the launcher prior to contact was faster or if the velocity of the target after contact was faster. Ratings of the resistance of the target were higher if the target remained stationary after contact and decreased with increases in target velocity after contact. When the target remained stationary, ratings of the resistance of the target were higher than were ratings of the force of the launcher. Ratings of the force of the target on the launcher were higher if the launcher reversed direction after contact than if the launcher stopped or continued motion in the same direction. White (2011b) replicated these findings and extended effects of the velocity of the initially moving object prior to contact and target velocity subsequent to contact to other types of stimuli for which perception of causality has been claimed (entraining, enforced disintegration, shattering). As a greater impetus would presumably result in a faster velocity, these patterns are consistent with an impetus heuristic. White (2011a) found the size of the gap and the presence of gap objects did not influence ratings of the force of the launcher on the target (cf. Hubbard & Ruppel, 2017, 2018), although the size of the gap and the presence of gap objects did influence ratings of whether the launcher caused motion of the target, and he concluded that perception of force and perception of causality are distinct components of visual interpretation. Thus, impetus appears to be linked to perception of causality and to perception of force, albeit in different ways.

In a launching effect, ratings of perceived force are similar to ratings of perceived causality (e.g., White, 2007), and this is consistent with a notion that impetus is a force imparted from the launcher to the target and that subsequently acts on the target. However, as discussed in White (2011a, 2014), ratings of causality and ratings of force can be dissociated (e.g., a launcher that contacted a target that remained stationary might be perceived as applying force to the target, but in the absence of any change in the target [e.g., initiation of motion, shattering, etc.] would not be perceived as having a causal effect on the target). Relatedly, although an association of perceived causality and perceived force is consistent with an impetus belief (i.e., when the magnitude of impetus is sufficient to affect the target), a dissociation of perceived causality and perceived force is also consistent with an impetus belief (i.e., when the magnitude of impetus is insufficient to affect the target). More critically, a consideration of perceived force suggests that representations underlying the launching effect (and perhaps other types of stimuli for which claims of perception of causality have been made, see Hubbard, 2013b) involve dynamic information rather than kinematic information. As described in Hubbard (2017b, 2019), there are two senses of "dynamic" in studies of perception and cognition: a nontechnical sense involving occurrence of change, and a technical sense involving description of forces. Dynamic information regarding representational momentum involves both senses, and implications of findings regarding representational momentum for an impetus heuristic, are relevant.

Representational momentum

The judged final location of a previously viewed moving target is often displaced slightly forward in the direction of anticipated motion (i.e., the target is judged as having traveled slightly further than it actually did), and this forward displacement has been referred to as *representational momentum* (for review, see Hubbard, 2005, 2018) and is shown in Fig. 3. Hubbard et al. (2001) compared representational momentum of a launched target to representational momentum of a variety of unlaunched control targets (e.g., the same target motion in the absence of a launcher, target motion in a direction orthogonal to launcher motion, etc.), and they found that representational momentum was smaller for launched targets than for unlaunched control targets. As representational momentum is decreased when observers expect a target to stop (Finke et al., 1986), a decrease in the forward displacement of a launched target is consistent with the hypothesis that observers expect that target to stop. More broadly, this decrease is consistent with the hypothesis based on naïve impetus theory that contact from the launcher imparted impetus to the target that was then dissipated by subsequent target motion. Once impetus imparted from the launcher to the target has dissipated below the level needed to maintain target motion, the target would be expected to stop, and this expectation would result in a decrease in representational momentum. Thus, representational momentum of a launched target could be interpreted as reflecting the cause or force of motion of that target; indeed, several examples of representational momentum described below have been suggested to reflect impetus.

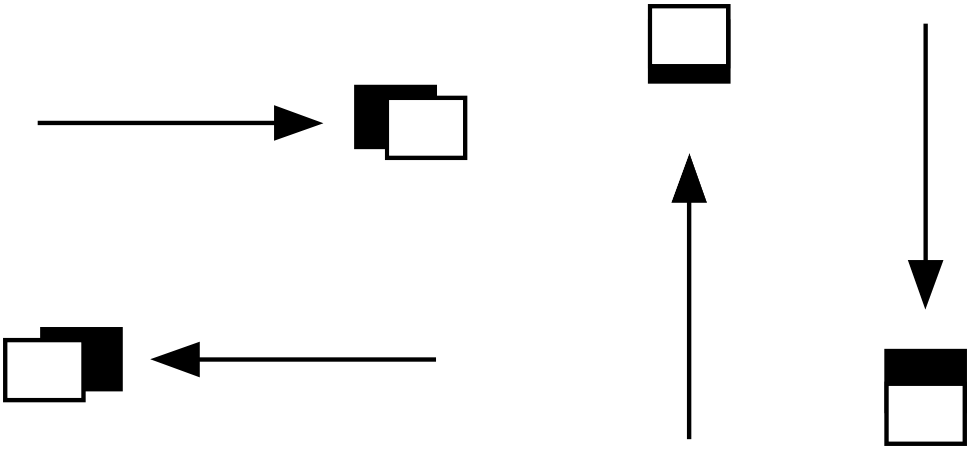

Fig. 3 Representational momentum. *Note*. The actual final location of a moving target is shown by a black box (arrows indicate the direction of motion), and the judged final location of that target is shown by a white box. For all directions, the judged vanishing point is in front of (beyond) the actual vanishing point. This forward displacement is larger for horizontal target motion than for vertical target motion, and is larger for descending target motion than for ascending target motion. Adapted from Hubbard (2005)

Hubbard and Ruppel (2002) reported several findings involving representational momentum that are consistent with a role of impetus in the launching effect. Representational momentum of a launched target was larger with faster launcher velocities, and this is consistent with White's (2007, 2009a) findings that faster launcher velocities were associated with higher ratings of force on the target. However, when the target did not move after contact, judgment of target location was not displaced in the direction of launcher motion, and this suggests that if the force (impetus) from the launcher is insufficient to overcome the inertia of a stationary target, then that stationary target will not move. Representational momentum of a launched target was decreased with increases in the distance traveled by the target, and this is consistent with the dissipation of impetus by subsequent target motion. When a launcher moved by systematic contraction and expansion (an organic motion similar to that of a caterpillar) and movement of the target coincided with a potential forward expansion of the launcher after the initial contact, representational momentum was similar to that in launching effect trials and less than in control trials. Interestingly, physical motion of a launcher might not need to actually occur, as Hubbard et al. (2005) found a decrease in representational momentum of a target when the launcher suddenly appeared adjacent to that target and the target immediately moved away; such an apparent launching might have resulted from perception of illusory gamma motion (i.e., the launcher appeared to expand outward from the center) that imparted impetus to the target.

The hypothesis that representational momentum of a launched target is influenced by impetus imparted from the launcher suggests that disruption of the imparting of impetus would eliminate the decrease in representational momentum. Thus, if the final location of the launcher and the initial location of the target were separated by a large spatial gap, representational momentum of the target would not be attributable to an impetus imparted from the launcher and would not be reduced relative to that of an unlaunched target. Hubbard and Favretto (2003) measured representational momentum when such a spatial gap was introduced, and there was no difference in displacement of targets in such a display from displacement of targets presented in isolation. However, if the spatial gap between the final location of the launcher and the initial location of the target was bridged by an intermediary object that was contacted by the launcher, crossed the gap, and contacted the target, or else was bridged by a stationary intermediary object that was contacted by the launcher on one end and was in contact with the target on the other end, then representational momentum of the target was reduced. The intermediary object appeared to provide a conduit for impetus to be conveyed from the launcher to the target, and the length of the spatial gap that an intermediary had to cross, or the length of a stationary intermediary that bridged the spatial gap, did not influence the representational momentum of the target. Such results are consistent with Michotte's (1951/1991) claim that the tool effect did not involve two separate launchings and with ratings of causality (e.g., Young & Falmier, 2008) and ratings of force (White, 2011a) when intermediary objects were presented in tool effect displays.

One interpretation of the results of studies on representational momentum and perception of causality is that representational momentum is influenced by perception of causality, but Choi and Scholl (2006) hypothesized that the decrease in representational momentum of launched targets in Hubbard et al. (2001) was due to the presence of two objects and one continuous motion rather than to perception of causality per se. As control conditions in Hubbard et al. (2001) were based on control conditions in Michotte (1946/1963), a similar objection could apply to Michotte's claims (i.e., apparent perception of causality reflected the presence of two objects and one continuous motion rather than perception of causality per se, cf. Michotte's discussion of ampliation). If Choi and Scholl's hypothesis was correct, then representational momentum of a target in an entraining effect (similar to a launching effect, but in which the initially moving object [henceforth referred to as an *entrainer*] does not stop upon contact, but continues moving in the same direction and at the same velocity, thus appearing to push the target) and a target in a launching effect should not differ, as the launching effect and the entraining effect each involve two objects and one continuous motion. However, Hubbard (2013a) found representational momentum of launched targets was less than representational momentum of entrained targets. This difference is consistent with an impetus notion: motion of a launched target was due to an initial impetus that dissipated with target motion, whereas motion of an entrained target was due to the entrainer continually pushing the target, and impetus from the entrainer that was dissipated by target motion was immediately replenished by the entrainer.

Two other findings in representational momentum literature are relevant to the impetus notion. Freyd and Jones (1994) found that representational momentum for objects that followed a curved path after exiting a spiral tube was larger than representational momentum for objects that followed a straight path after exiting a spiral tube. Although larger representational momentum for targets on a curved path might seem inconsistent with smaller representational momentum for launched targets, both results are consistent with the impetus notion: Larger representational momentum for the spiral path suggests that participants were anticipating and extrapolating a spiral path (as representational momentum is larger when targets move in an expected direction rather than in an unexpected direction, Hubbard, 1994), and smaller representational momentum for a launched target suggests participants were expecting such a target to stop. Kozhevnikov and Hegarty (2001) suggested that larger forward displacement of smaller ascending targets was more consistent with a representational impetus than with a representational momentum, but as discussed in Part II, their view of impetus differs from that discussed in naïve impetus theory. Interestingly, in Freyd and Jones (1994) and in Kozhevnikov and Hegarty (2001), participants responded in ways consistent with an impetus notion even when they had explicit knowledge of relevant Newtonian principles. Also, unlike in experimental tasks involving perception of causality or perception of force, experimental tasks involving representational momentum did not mention causality or force, and so the possibility of demand characteristics was diminished.

Part II: Properties, applications, and implications

The studies discussed in Part I reveal a history of investigation of the impetus notion and are consistent with the idea that a belief in impetus can be used as a heuristic. Indeed, the possibility of an impetus heuristic has been previously suggested in literature on naïve physics and in literature on representational momentum. Part II considers how an impetus heuristic is related to Newtonian laws, why an impetus heuristic might be used, whether the impetus notion involves a heuristic or an implicit physical theory, alternatives to the impetus notion, development of the impetus notion, the relationship of a belief in impetus to a property transmission heuristic, the relationship of an impetus heuristic to perception of causality, when impetus might be imparted, and some potential future issues for research on the impetus notion.

Relationship to Newtonian laws

As noted earlier, the notion of impetus is not consistent with Newton's laws (for review of Newtonian physics, see Crowell, 2008; Mahajan, 2020; McDougal, 2012). The notion of impetus involves a force that is acquired and then gradually dissipates, and the idea of such a force is inconsistent with Newton's first law of motion, which states that an object at rest will continue at rest, and that an object in motion will continue in motion, unless that object is acted upon by an outside force. Furthermore, the causal asymmetry (White, 2006) and the force asymmetry (White, 2009a) are inconsistent with Newton's third law of motion, which states that a force exerted on a body is opposed by an equal force in the opposite direction (i.e., an equal and opposite reaction). The force-resistance asymmetry (Hubbard & Ruppel, 2017) is similarly inconsistent with Newton's laws, as force and resistance are the same physical quality but appear to be different psychological qualities (e.g., force is more active and resistance is more inactive or passive; White, 2009a). Additionally, the behavior of physical objects in dynamic systems is determined by multiple parameters (e.g., center of mass, distribution of mass, angular momentum, conservation, inertia, etc.), but observers typically explicitly consider only one dynamically relevant dimension for any given stimulus (e.g., Gilden & Proffitt, 1989).[3] Importantly, the launching effect, which has been claimed to reflect a perception of causality, is influenced by several variables that are not related to Newtonian laws regarding collisions of physical objects (Hubbard, 2013b, 2013c), and this is more consistent with the use of a heuristic.

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[3] An apparent exception to this is found in representational momentum literature, in which relevant physical dynamics such as gravity (Hubbard, 2020) and friction (Hubbard, 1995a), as well as momentum, can combine to determine the direction and magnitude of displacement in the representation of target location. Additionally, many other types of information (e.g., expectations of a change in direction of target motion, knowledge of the type or category of the target [e.g., steeple or rocket]) can also influence displacement (for review, see Hubbard, 2005, 2018). However, such multiple influences on displacement occur automatically and do not require explicit or deliberative consideration of the type presumably required in most studies in naïve physics.

Perhaps the physical properties of moving targets that are most likely to be confused with impetus or replaced by an impetus notion in the mental representations of those targets are inertia and momentum (cf. Halloun & Hestenes, 1985). Inertia is a tendency for a moving object to continue in motion, or for an object at rest to remain at rest, unless that object is acted upon by an outside force. Given this, it is not clear how an object at rest could possess impetus, as a stationary object would presumably have dissipated any impetus that might have been previously imparted to it. Although inertia is a property of moving objects and of stationary objects, the impetus notion only applies to moving objects. Similarly, the momentum of an object is the product of that object's velocity and mass, and in the absence of an outside force that reduces either velocity (e.g., friction with the surface the object is moving across or resistance from the medium the object is moving through) or mass, momentum would remain constant and not decrease (i.e., not appear to dissipate). As noted earlier, a key feature of impetus is that it is believed to dissipate in the absence of any outside force that is applied to a moving target. However, the idea of a force such as impetus that spontaneously dissipates in the absence of any change in an outside force applied to the target is inconsistent with, and distinguishes impetus from, inertia and momentum. Interestingly, in colloquial language "impetus" appears to be used to refer to starting a new activity or state (i.e., a change), whereas "inertia" and "momentum" appear to be used to refer to a continuation (i.e., a lack of change) of a previous activity or state.

Why an impetus heuristic?

Given that impetus does not correspond to a valid physical principle, it might appear curious that observers would appeal to an impetus heuristic. Indeed, White (2012c, p. 1018) asks, "if we are going to abstract a dynamic theory of motion, why not abstract the correct one, that objects slow down because of friction and air resistance?" This is an important question, and it can now be answered. Consider the following example from Hubbard (2017b, 2019): If a stationary object is resting on a surface, and that object is pushed with sufficient force, it will move a short distance and then stop. The behavior of the pushed object can be predicted and correctly explained by a complex consideration involving multiple interacting variables (e.g., mass of the object, friction of the object with the surface, air resistance, etc.) or by a simpler consideration involving a single variable (e.g., an impetus that dissipates). In the latter case, a belief in impetus provides a heuristic that lets an observer make approximately correct predictions regarding the behavior (motion) of a pushed object (e.g., the object will move a short distance and then stop, stronger or more forceful pushes lead to the pushed object traveling farther before stopping), but without having to consider all of the relevant variables regarding mass, friction, and so forth. Observers would have seen many examples of pushed objects (and pushed many objects) during their lives, and such experience is consistent with the hypotheses that belief in impetus arises from everyday experience (Kozhevnikov & Hegarty, 2001)[4] and that visual perception of causality and perception of force are related to previous haptic experience (White, 2012b).

An impetus heuristic correctly predicts some physical outcomes (e.g., a pushed object moves a short distance and then stops) but does not correctly predict other physical outcomes (e.g., an object that exits a curved tube does not continue in a curved path). Although examples in which the use of an impetus heuristic results in an incorrect prediction might seem to disconfirm the notion of an impetus heuristic, such examples can actually offer compelling evidence that such a heuristic is used, if participants' responses match those predicted by the notion of impetus. Indeed, the content of incorrect answers to problems often sheds light on the strategies of experimental participants in solving those problems and on any heuristics that are used (e.g., see Gigerenzer et al., 2011; Kahneman et al., 1982). Relatedly, if an impetus heuristic exists, then presumably it is adaptive. It might be that situations in which incorrect predictions are made are encountered much less frequently (or not at all) in everyday life than are situations in which correct predictions are made. If so, then it is likely that the consequences of situations in which an impetus heuristic leads to incorrect predictions are not severe enough to be selected against, and the consequences of situations in which an impetus heuristic leads to correct predictions are sufficiently beneficial to outweigh the costs of incorrect predictions in other situations. Some incorrect predictions would presumably have little or no relevance to survival of an observer (e.g., whether a pendulum bob falls along a parabola or continues along a curved path before dropping straight down), and so there would be no pressure to select against such predictions.

Heuristic or implicit physical theory

It has been previously suggested that the impetus notion can be used as a heuristic (e.g., Kozhevnikov & Hegarty, 2001). The impetus notion is consistent with several definitions and characterizations of heuristics, including Kahneman and

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[4] Relatedly, it has been suggested that representational momentum (Hubbard, 2006, 2019), as well as representational gravity (Hubbard, 2020), arise from subjective aspects of everyday experience (e.g., mass is usually experienced as weight, and so effects of mass are represented as effects of weight, and so regardless of the direction of target motion, target mass influences displacement only along the axis aligned with implied gravitational attraction).

Frederick's (2002) suggestion that heuristics assess a target attribute via another property (attribute substitution); Shah and Oppenheimer's (2008) suggestion that heuristics rely on effort reduction and use of less information; Gigerenzer's (2008) suggestion that heuristics are frugal (i.e., use only a part of the available information), satisfice rather than optimize, and focus on situations in which an answer is needed relatively rapidly; and Gigerenzer and Gaissmaier's (2011) definition of a heuristic as a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than do more complex methods. Use of an impetus notion as a heuristic is consistent with such definitions and characterizations, as the impetus heuristic substitutes the impetus notion for Newtonian object properties, reduces effort by focusing on a single factor (i.e., an impetus that dissipates) rather than a complex set of factors (e.g., mass, resistance, etc.), satisfices rather than provides an optimal prediction (e.g., it is sufficient to know a pushed object will move a short distance and then stop), and as demonstrated by studies on perception of causality, occurs very rapidly. Indeed, many studies reviewed in Part I suggest the impetus notion provides a simple strategy for perception and problem solving analogous to the simple strategies used by the representativeness, availability, and other well-known heuristics.

It has also been suggested that the impetus notion involves an implicit physical theory (e.g., McCloskey, 1983). An implicit physical theory is consistent with an observation that responses in many studies of naïve physics that implicated impetus seemed to involve deliberation, whereas many heuristics seem to be activated automatically. However, Gigerenzer (2008) suggests that heuristics can be used with or without awareness, and this is consistent with an argument that the presence or absence of deliberation is not a critical consideration in whether or not the impetus notion can be used as a heuristic. The impetus notion might be consistent with or included in a larger physical theory that goes beyond any specific stimulus, but which can be automatically applied when an individual is presented with a specific type of stimulus configuration. Such an application might be in the form of an unconscious inference similar to that suggested by von Helmholtz (1867) and Rock (1983) and similar to that suggested to underlie the constancies (e.g., Walsh & Kulkowski, 1998) and size-distance invariance (e.g., Epstein et al., 1961). Thus, the presence of the impetus notion in both an implicit physical theory and in a heuristic is not necessarily incompatible, as an observer might have a notion of impetus as part of a larger implicit physical theory and also automatically apply that notion in the perception or simulation of dynamic physical objects. In other words, a belief in impetus matches the features and characteristics of a heuristic (e.g., being frugal and fast), but it is also possible that information regarding a belief in impetus is in the form of an implicit theory.

Alternatives to an impetus notion

There are at least three alternatives to an impetus notion that can be considered, and these include the Kinematics Specifies Dynamics model, noisy Newton model, and "on-the-fly" reasoning. It is suggested that the first and second alternatives do not offer convincing evidence against an impetus heuristic and that the second and third alternatives are consistent with an impetus heuristic.

Kinematics Specifies Dynamics The first alternative involves the Kinematics Specifies Dynamics (KSD) model suggested by Runeson and Frykholm (1983). In this approach, variables involved in the collision of two objects (e.g., as in a launching effect) are of two types: kinematic (e.g., velocity) and dynamic (e.g., mass). Kinematic variables can be directly observed, but dynamic variables usually cannot be directly observed and must be inferred; even so, the values of kinematic variables usually constrain the range of possible values of dynamic variables. There is evidence that observers use heuristics in making judgments of dynamic values such as the (implied) mass of objects that are involved in collisions (e.g., the object that ricochets farther or that travels faster after collision is less massive; Gilden & Proffitt, 1989). However, the KSD model is challenged by findings of a motor object bias (in which in displays of colliding objects the launcher [referred to as the *motor object*] is always believed to be heavier than the target regardless of whether the launcher possessed more or less mass than the target, e.g., Cohen, 2006; Flynn, 1994), and such a bias is not consistent with Newtonian principles. Always attributing greater mass to the launcher is consistent with always attributing more causality and more force to the launcher, that is, consistent with causal asymmetry and with force asymmetry, respectively. Indeed, the motor object bias appears more consistent with an impetus notion than with the KSD model. Furthermore, although kinematic information might be used heuristically to derive dynamic information (Gilden, 1991), it would seem simpler to use a heuristic (such as an impetus notion) to directly predict or evaluate object motion.

Noisy Newton A second alternative involves a noisy Newton model as suggested by Sanborn et al. (2013). In this approach, responses are based on a combination of noisy sensory information, Bayesian inference, and Newtonian principles. The noisy Newton model suggests observers have internal representations of physical constraints that are based on an accurate understanding of Newtonian principles, which are then combined with noisy information from the sensory systems to make Bayesian inferences about the physical situation. Sanborn et al. suggest such an approach can be applied to any situation that requires making an inference from observed variables, and they focus on the case in which two objects collide and observers make inferences regarding the relative masses of the objects or regarding causality. The impetus heuristic also addresses the case in which two objects appear to collide, and the noisy Newton model and the impetus heuristic both address the launching effect. It is not clear how the noisy Newton model might address other types of perception of causality, but the impetus notion has been applied to the entraining effect (Hubbard, 2013a) and the tool effect (Hubbard & Favretto, 2003), as well as to stimuli that do not involve an explicit collision (e.g., a ball exiting a curved tube). More critically, as the noisy Newton model involves noisy sensory information, Bayesian inference, and Newtonian principles, it is a more complex model that would require more cognitive processing than would a simpler impetus heuristic that involves only the single parameter of an impetus that dissipates.

Sanborn et al. compare performance of their noisy Newton model to the performance of two heuristics (involving pre- and post-collision velocity and whether an object ricochets after collision), but they do not compare the noisy Newton model to an impetus heuristic. Importantly, a noisy Newton model assumes an accurate knowledge of Newtonian principles, but ample evidence suggests observers have not necessarily accurately internalized Newtonian principles (e.g., momentum, Hubbard, 2018; gravity, Hubbard, 2020). In the absence of an accurate representation of Newton principles, the validity of a noisy Newton model is questionable. Additionally, Sanborn et al. acknowledge the noisy Newton model does not account for findings regarding the perception of force. However, an impetus heuristic is consistent with many of the findings regarding perceived force and does not require an accurate representation of Newtonian principles. Relatedly, a noisy Newton model does not address the differences between perceived force and perceived resistance. A noisy Newton model appears inconsistent with findings of causal asymmetry and force asymmetry, as increased uncertainty would presumably result in a larger variance in responses rather than in a bias in a specific response direction; however, an impetus heuristic is consistent with causal asymmetry and force asymmetry. Even so, a noisy Newton approach is not necessarily inconsistent with an impetus heuristic if the specification of an accurate understanding of Newtonian principles is dropped, but it is not clear what advantage such a model might have over a simpler impetus heuristic.

"On-the-fly" reasoning A third alternative involves on-the-fly reasoning as suggested by Cooke and Breedin (1994a, 1994b; but see Ranney, 1994). In this approach, judgments and explanations are constructed "on-the-fly" (i.e., in real time) from various contextual cues (e.g., whether the stimulus is stationary or in motion, available response options) and other knowledge (e.g., previous experience with similar stimuli, Newtonian or other beliefs regarding motion). This approach is based in part on findings that familiarity with the stimulus can influence observers' judgments and that familiar problems can evoke situation-specific knowledge better than can more abstract problems (e.g., Kaiser et al., 1986). However, as experimental participants with little or no formal training in physics are less likely to realize that physical situations with different features can involve similar principles (e.g., Chi et al., 1981; see also Donley & Ashcraft, 1992), such participants might be less likely to apply a correct (Newtonian) response in naïve physics tasks that involve different features but the same principle (cf. a ball rolling off a cliff and a pendulum line cut at the bottom of the swing, a ball or water exiting from a curved tube). Rather, such participants might be more likely to use reasoning that is based on contextual cues (e.g., features) and other knowledge or beliefs, and this reasoning could involve a heuristic based on the impetus notion. As noted earlier, heuristics can be used when an answer needs to be obtained quickly and frugally, and "on-the-fly" reasoning using an impetus heuristic could provide an excellent example of such quick-and-frugal problem solving.

Development of an impetus notion

The majority of studies on beliefs regarding impetus or on a potential impetus heuristic have been carried out using college-aged or adult populations. A small number of studies have examined perception of causality in infancy (for review, see Hubbard, 2013b), and several studies suggest that sensitivity to causality in the launching effect emerges by approximately 6 months of age (e.g., Leslie & Keeble, 1987; Newman et al., 2008; Schlottmann et al., 2012), although one study suggests sensitivity to causality in a launching effect can emerge as early as 4.5 months if visual perception matches action experience (Rakison & Krogh, 2012). Interestingly, an emphasis on whether visual perception matches action experience is consistent with theories of visual perception of causality and visual perception of force that suggest such perception is based on haptic experience of motor actions upon objects (e.g., White, 2012b), and the time frame in which infants develop the ability to reach toward and grasp objects (e.g., Thomas et al., 2015) seems similar to the time frame for emergence of perception of causality. When an impetus heuristic might emerge within development is not known, but the framework presented here predicts an impetus notion would develop soon after the ability to grasp and act upon objects. No studies have yet examined whether infants have a notion that corresponds to impetus, but it could be hypothesized that an infant's initial experience with grasping, hitting, and other motor interactions provides the haptic (action) experience that forms the basis for the notion of impetus, which in turn would relate to perception of causality and influence of the impetus notion in other domains.

Impetus and property transmission

White (2012c) rejected a potential impetus heuristic as an account of the data from experiments on naïve physics and experiments on representational momentum. Instead, he suggested the results from such experiments can be accounted for by an application of his broader property transmission hypothesis (in which properties of the effect object often resemble properties of the causal object, White, 2009b), which he referred to as *actions-on-objects*. According to the actions-on-objects hypothesis, an understanding of what happens when one object appears to exert a force on another object is based on previous experience of the observer in generating motions of objects by acting on those objects. Such previous experience involves haptic information (involving force) that is subsequently activated when an observer views an object that is acted upon by another object, and this leads to a visual perception of causality and of force (White, 2012b; but see Hubbard, 2012; White, 2012a). White (2012c) provided descriptions of how such an actions-on-objects explanation could account for findings previously attributed to a belief in impetus (e.g., a person whirling an object at the end of a string is applying force to the object and constraining it to move in a circle). The kinematic properties of the system are transmitted to the object, and when the string is cut, the object retains those properties and so continues to move in a curvilinear path. Similarly, decreased representational momentum of a launched target is attributed to the common observation that objects whose motion is externally caused slow down and stop once those external causes are removed.[5]

White (2012c) portrays the impetus hypothesis and the actions-on-objects hypothesis as mutually exclusive, but as noted by Vicovaro et al. (2020), impetus attributed to the causal object could be the property of the causal object that is perceived to be transmitted. In order to evaluate this possibility, a closer look at the criteria for property transmission, and whether an impetus notion meets those criteria, is needed. White (2010) specified three criteria for property transmission: activity must be occurring, there must be observable cues to transmission of a force or energy from one object to another, and there should be a time-ordered resemblance between properties of the causal object and properties of the effect object. An impetus notion fulfills each of these criteria, as impetus arises from launcher activity (motion), is transferred to the target (at contact), and subsequent target motion resembles previous launcher motion (similar direction and velocity). Of course, as impetus is not a valid physical principle, there is no impetus actually transmitted (but in computer animations of launching effect stimuli, no force is transmitted, either), but if observers attribute impetus to the launcher and believe that impetus is transferred to the target, then that belief could be sufficient to trigger an impetus heuristic. Such an account is consistent with White's (2012b) claim that visual perception of causality and force are based on previous haptic experience and with Kozhevnikov and Hegarty's (2001) suggestion that an idea of impetus could arise from everyday experience; such a grounding in past experience could help explain why naïve concepts are often so difficult to overcome.

A transmission of impetus can account for patterns of representational momentum in the launching effect and in the entraining effect in Hubbard (2013a). Impetus of the launcher or entrainer is transmitted (imparted) to the target. As motion of launchers and entrainers is presumably internally or self-generated (i.e., a launcher and an entrainer appear self-propelled), any force causing movement of those objects is continually maintained (rather than dissipated) while those objects are in motion. The action-upon-object occurs only during the time the launcher or entrainer is in contact with the target. Thus, in a launching effect, the action-upon-object occurs only briefly, whereas in the entraining effect, the action-upon-object is prolonged. As long as the action-upon-object is maintained, any impetus present does not dissipate (and representational momentum of the target would not decrease), but once the action-upon-object ceases, any impetus present would begin to dissipate (and representational momentum of the target would decrease). Also, representational momentum of entrainers was smaller than representational momentum of launchers. The decrease in representational momentum of entrainers is consistent with a longer and more sustained pushing of the target (i.e., a continual transference of the force of the entrainer to the target). Interestingly, in the launching effect and in the entraining effect there seems to be a conservation (or constant overall level) of impetus within each effect, with larger representational momentum for launchers and entrained targets and smaller representational momentum for entrainers and launched targets.

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[5] In his discussion of representational momentum and the actions-on-object hypothesis, White (2012c) states "different extrapolations are made depending upon whether the object's motion is perceived as internally or externally caused. Apart from that, displacement phenomena do not depend on the representation of dynamic properties" (p. 1022), "it is the matched kinematic characteristics, not the dynamic properties that determine them, that mediate the trajectory extrapolation" (p. 1023), and "there is no evidence that displacement is affected by a concept of acquired force" (p. 1024). Such statements are not entirely correct, as displacement reflects numerous dynamic properties (e.g., see Freyd, 1987; Hubbard, 1995b, 2005, 2015a). For example, White discusses how slowing of a physical object is due to friction, but does not acknowledge that friction is a dynamic force that influences displacement (e.g., see Hubbard, 1995a, 1995b). More broadly, representation of dynamic properties, and the influence of those dynamic properties on the representation of location, is exhibited in both representational momentum (Freyd, 1987; Hubbard, 2019) and representational gravity (Hubbard, 2020).

Impetus and perception of causality

A long philosophical tradition from Hume and Kant suggests that causality cannot be directly perceived but must be inferred (for overviews, see White, 1990; Young, 1995). Michotte (1946/1963) challenged this tradition, and given his findings on perception of causality in the launching effect and in other related effects, he suggested that under specific circumstances observers can directly perceive causality. However, the use of an impetus heuristic in perception of the launching effect suggests that, contrary to Michotte, observers do not directly perceive causality, and the reason why is straightforward: If observers appeal to an impetus heuristic, then they cannot be accurately perceiving causality, because as noted earlier, impetus does not correspond to a valid physical principle. Furthermore, if perception of causality in the launching effect is based at least in part on previous haptic experience as suggested by White (2012b), then that would not be consistent with a direct perception of causality but would be more consistent with a top-down mediation of perception in which causality is inferred based upon that haptic experience. The rapidity with which an inference of causality occurs in the launching effect (or in other displays for which perception of causality is claimed) might mislead some researchers into thinking no such inference occurs, but as noted earlier, the notion of a rapid inference has a long history in perceptual psychology (e.g., the "unconscious inference" of von Helmholtz, 1867; Rock, 1983) and is found in other areas of perception (e.g., constancies, Walsh & Kulkowski, 1998; size-distance invariance, Epstein et al., 1961). Indeed, such a rapid inference might potentially be viewed as a matching of perceptual input to a procedure or a template.

It is possible that observers experience a perception of causality when viewing a launching effect display not because those observers perceive causality, but because behavior of the launcher and target trigger implementation of an impetus heuristic (cf. Hubbard, 2004, 2013b). Although such an account is inconsistent with the interpretation suggested by Michotte (1946/1963), it is not inconsistent with the data reported by Michotte. An impetus-based account gives no reason to question the subjective reports of observers, but rather offers an alternative way to interpret those reports. Relatedly, White (2012c, p. 1025) suggests in his discussion of naïve physics experiments that an impetus notion is not necessarily evoked when observers have correct knowledge regarding the behavior of a physical system; however, he incorrectly suggests "there is no evidence that a theory of impetus is involved in displacement phenomena." Indeed, evidence of impetus has been suggested in at least three findings in representational momentum literature: smaller displacement for launched targets (Hubbard, 2013a; Hubbard et al., 2001; Hubbard & Ruppel, 2002), larger displacement for targets that followed a curvilinear path after exiting a spiral tube (Freyd & Jones, 1994), and larger displacement for smaller ascending targets (Kozhevnikov & Hegarty, 2001). An impetus heuristic has not been claimed as contributing to other instances of representational momentum; effects of an impetus heuristic on representational momentum might occur only for targets whose motion was constrained or influenced by other stimuli, as other targets would be perceived as exhibiting internally or self-generated motion, and so dissipation of impetus would not apply (although see Kozhevnikov & Hegarty, 2001).[6]

When impetus might be imparted

Naïve impetus theory suggests the motion path of a target that was previously constrained or influenced by an external object appears to exhibit effects of the same constraint or influence even after that constraint or influence has been removed. In examples from studies of naïve physics in which a target object exits from a curved tube or is cut from the end of a pendulum or a whirling string, and in examples from studies of perception of causality and perception of force in which a target object is contacted or influenced by another object, it is clear how impetus could be imparted to the target. However, Kozhevnikov and Hegarty (2001) presented ascending or descending targets, and as their targets were presented in isolation (i.e., there was no other stimulus in the display that could have constrained or influenced motion of a target), it is not initially clear how, from where, or why impetus might have been imparted to the target. Kozhevnikov and Hegarty argued that the influence of implied gravity resulted in an increasing impetus for descending targets and a decreasing impetus for ascending targets, and furthermore, that the impetus notion suggested that a more massive object would gain and lose impetus more quickly than would a less massive object. As a consequence, a more massive object would be believed to descend faster (resulting in larger representational momentum) and to ascend slower (resulting in

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[6] Based upon the results of Freyd and Jones (1994) and Kozhevnikov and Hegarty (2001), it might be suggested that what has been referred to as representational momentum is really a representational impetus. However, momentum offers a more appropriate analogy than does impetus for at least two reasons. First, many studies of forward displacement presented targets in isolation, and so presumably motion of those targets was self-generated (and there was no reason to attribute target motion to influence from another object). Second, representational momentum of an isolated target is usually not influenced by trajectory length (unless the trajectory is approaching a barrier such as the edge of the stimulus display), and this is more consistent with momentum (which does not dissipate in the absence of an external force) than with impetus (which does dissipate in the absence of an external force). To the extent that an extrapolation mechanism that underlies representational momentum can be influenced by expectations, knowledge, and beliefs of an observer (see Hubbard, 1995b, 2005, 2018), then a belief in impetus is just one of several sources of information that potentially contribute to extrapolating motion trajectory.

smaller representational momentum) than would a less massive object. Such an argument suggests that a constraining effect of gravity during target motion might operate similarly to the constraining effect of a spiral tube on motion of a ball prior to exiting that tube.

Kozhevnikov and Hegarty's (2001) view of impetus differs from that in naïve impetus theory, as they suggested that impetus can be added to or subtracted from the target during target motion, whereas naïve impetus theory suggests impetus is imparted only at the beginning of target motion and then dissipates with target motion. However, this difference is not as clear as it might initially appear, as examples in naïve physics literature seem to involve an acquisition of impetus during the initially constrained target motion (e.g., a ball still in a curved tube or an object still whirled on a string), the effects of which can only be clearly observed once the constraint is removed (e.g., after the ball has exited the tube or the string is cut). The possibility that impetus might be acquired during target motion is consistent with the earlier speculation that an entrainer replenishes any imparted impetus that is dissipated from motion of an entrained target and that the actions-on-objects hypothesis allows the influence of another stimulus on the target for as long as that other stimulus is in contact with the target. Given this, it might be necessary that the characteristics of impetus specified by naïve impetus theory (i.e., imparted only at the beginning of target motion, dissipates with target motion) be revised to include a longer acquisition of impetus and the possibility of adding or replenishing impetus during subsequent target motion. Additionally, whether contact from another object is necessary for imparting of impetus (and perception of force) should be reconsidered in light of the claim that gravity contributes to attribution of impetus (cf. representational gravity, Hubbard, 2020).

The future of impetus

An impetus heuristic is consistent with a broad range of findings from studies on naïve physics, perception of causality, perception of force, and representational momentum. An impetus heuristic can be applied to solving problems related to predicting or judging the behavior (e.g., motion) of a physical object in a dynamic system and seems more likely to be used when another object acts in some capacity on the target object (e.g., constraining direction of motion, colliding with and launching into motion, etc.). As a heuristic can be used with or without awareness (Gigerenzer, 2008), application of an impetus heuristic can occur automatically (in causal impression or causal perception) or deliberately (in causal judgment). Also, application of an impetus heuristic need not be limited to physical objects in motion, but could apply more broadly to cases in which a stimulus changes in some property other than physical location. In these cases, the motion path would be metaphorical or analogical (e.g., a spatial coordinate system can represent values of multiple variables, and changes in these values result in movement and a motion path in that coordinate space), and a belief in impetus might influence judgments regarding that movement and motion path. Indeed, such a broader application would be consistent with claims regarding the importance of spatial metaphor and analogy in cognition (e.g., Lakoff & Johnson, 1980; Suiter & Schubert, 2018) and would parallel the extension of momentum-like effects beyond representational momentum to include psychological momentum or behavioral momentum (e.g., Hubbard, 2015a, 2015b). Such a broader application could have far-reaching effects and potentially offer a unifying mechanism across a variety of types of stimuli.

There are at least two domains in addition to those already discussed in which effects of impetus related to a metaphorical motion path might occur. The first domain involves goal pursuit. Just as the impetus heuristic suggests that motion of a target begins when impetus is imparted and stops when impetus drops below the level needed to maintain motion, so too might an impetus heuristic be applied when a new behavior (that is caused by an external source) begins but subsequently stops (e.g., a behavior initiated by a New Year's [or other] resolution might begin at a robust level, but the frequency or magnitude of that behavior decreases and subsequently stops as motivation [i.e., impetus] dissipates). In other words, motivation for goal pursuit might function in a typical impetus-like manner (e.g., an initial "imparting" of motivation followed by a subsequent "dissipation" of that motivation), and the extent to which an impetus heuristic might be applied to goal pursuit or perhaps other social behaviors could be a fruitful area of future investigation. The second domain involves music. Larson (2012) speculated about the existence of a musical inertia in which pitches or durations continue in the current pattern, and Hubbard (2017a) suggested such a continuation might be considered as a type of musical momentum analogous to psychological momentum or behavioral momentum. Indeed, such continuations have been reported (e.g., during a silent gap in a familiar melody, listeners report an imaged continuation of the melody, Kraemer et al., 2005; during the gap between tracks on a familiar CD, listeners report anticipatory imagery of the next track, Leaver et al., 2009). More broadly, a musical impetus might also involve repetition of previous pitch or rhythm patterns.

Future research on the possibility of an impetus heuristic should also examine potential boundary conditions beyond which such a heuristic would not apply. One generally accepted boundary condition is that impetus is attributed to an object when subsequent motion of that object is perceived to be externally caused and not when subsequent motion of the object is perceived to be autonomous or self-generated.

However, the idea of "externally caused" is inconsistent across the literature, and this can be seen in the example of an object dropped from a horizontally moving object. McCloskey et al. (1983) claimed such a dropped object does not acquire impetus from being released from the moving object, whereas Kozhevnikov and Hegarty (2001) claimed such a dropped (falling) object acquires impetus from gravity. Other potential boundary conditions are that the observer judging a physical stimulus is presented with too much information (e.g., a dynamic stimulus that must be simplified) or too little information (e.g., a static stimulus that must be supplemented) and that motion through some type of coordinate space is required (as a stationary target would not possess impetus). Importantly, given the range of domains and types of stimuli to which an impetus notion might be applied, a single experiment or set of experiments would not be sufficient to falsify the general impetus notion; rather, what would be required for falsification is a more nuanced response in which the impetus notion is evaluated in different domains and types of stimuli to which it might be applied. Thus, a lack of application of the impetus notion in one domain or type of stimuli would not necessarily falsify the potential application of the impetus notion for other domains or types of stimuli.

Part III: Summary and Conclusions

Since the initial investigations of naïve physics, a belief in impetus has been suggested to influence observers' understanding of the behavior of physical objects in dynamic systems involving motion. Evidence supportive of an impetus heuristic has been reported in the form of predictions or judgments regarding the motion path of an object (in studies of naïve physics), how causal one object is of the motion or behavior of another object (in studies of perception of causality), the force that one object exerts upon another object (in studies of perception of force), and the final location of a moving object (in studies of representational momentum). Such predictions and judgments are consistent with a belief in impetus and suggest the motion path of an object is believed to be constrained or influenced by an external stimulus, and that such influence strengthens with the continued presence of the constraint (e.g., gravity) or weakens (dissipates) after the constraint (e.g., a curved tube in which motion occurs) is removed or with object motion after the interaction (e.g., after a previously stationary target is launched into motion). Such an impetus heuristic can in some cases yield predictions of motion paths that are approximately correct but require less effort than would predictions based on consideration of all the relevant physical variables. Such an impetus heuristic would be triggered automatically and influence both causal impression or perception and causal judgment; whether beliefs regarding impetus reflect a consistent theory or different situation-specific beliefs regarding physical phenomena would not necessarily impact the use or consequences of an impetus heuristic.

Impetus does not correspond to a valid physical principle, and so the existence and use of an impetus heuristic significantly challenges claims that observers can visually perceive causality. Similarly, impetus appears to influence visual perception of force and localization of targets; use of an impetus heuristic in judgments of force significantly challenges claims that observers can visually perceive force, and the influence of an impetus heuristic on at least some examples of representational momentum suggests that extrapolation mechanisms that give rise to displacement are cognitively penetrable to a belief in impetus. An impetus heuristic appears more likely to be used when properties of the motion path of an object are attributed to an influence imparted from another object, but this and other potential boundary conditions are not yet clear. The notion of impetus might be acquired from haptic experience with objects in everyday life, and in addition to use in prediction or judgment of actual motion paths of physical objects, an impetus heuristic might have broader applications to metaphorical types of motion and motion paths such as those involving goal pursuit or involving perception or performance of music. An impetus heuristic offers one way in which observers represent, predict, and judge dynamic qualities of objects in their environment, a way that does not require representation of multiple or objective physical principles, but that generally allows generation of approximately correct answers with a minimum of cognitive effort or resources. Furthermore, an impetus heuristic appears simpler and accounts for a wider range of data than do alternative accounts.

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Portions of this paper were presented at the 61st Annual Meeting of the Psychonomic Society (November, 2020). There is no known conflict of interest to report. The author thanks two anonymous reviewers for helpful comments on a previous version of the manuscript.

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