**May the Force be against you:**

**Better sensitivity to speed changes that appear to resist gravity**

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Running Head: Sensitivity to speed changes resisting gravity

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**Abstract**

Beyond seemingly lower-level features such as color and motion, visual perception also recovers properties that are more commonly associated with higher-level thought — as when an upwardly accelerating object is seen as self-propelled, and resisting the force of gravity. Past work has explored how speed changes drive the perception of physical forces, but might the reverse *also* be true? Does seeing a speed change as self-propelled make us more likely to notice it in the first place? In four experiments, online observers were more sensitive to objects' accelerations when they moved upward (i.e. when those accelerations opposed gravity), and they were more sensitive to objects' decelerations when they moved downward (i.e. when those decelerations appeared as 'braking' against gravity). We conclude that the perception of self-propelledness is not merely an 'endpoint' in visual processing, but rather determines the perception of other, seemingly lower-level, features of how objects move.

**Keywords:** Perception of forces; Perception of gravity; Perception of acceleration; Perception of animacy; Perception of causality

When we see a moving object, we readily perceive a great deal of information about its motion, including its direction, speed, and rate of acceleration. But beyond these seemingly lower-level features, there is also evidence that we see objects' movements in terms of properties which are more traditionally associated with higher-level thought — such as the *physical forces* acting on and within them. For example, when observers view point light displays in which an actor lifts an object, they use acceleration cues to recover information about the object's weight, and about the amount of force that was required to lift it (e.g. Runeson & Frykholm, 1987; Valenti & Costall, 1997). Moreover, work on the perception of animacy has long emphasized that objects that move as though they are self-propelled (i.e. moving without the visible application of an external force) are reflexively seen as alive (for reviews, see Scholl & Gao, 2013; Scholl & Tremoulet, 2000) — with apparently self-propelled motion capturing attention in adults (e.g. Pratt et al., 2010), infants (e.g. Luo & Baillergeon, 2005), and even in non-human animals such as chickens (e.g. Di Giorgio et al., 2021).

**<u>Does the perception of forces interact with other forms of visual processing?</u>**

We have a good understanding of the "upstream" visual motion parameters that cause physical forces to be perceived, and of some of the "downstream" consequences of perceiving forces for memory (e.g. Hubbard, 2005), and reasoning (e.g. Kubricht et al., 2017). However, to our knowledge, there has been little exploration of the possible functional effects of perceiving forces *within perception itself*: Seeing an object accelerate may drive the perception of forces acting upon it, but the reverse may *also* be true — such that the perception of an object's movement as driven by an internal versus external force may in turn determine basic visual sensitivity to whether or not the object is changing speed. Such interactions with other forms of visual processing would argue against the characterization of forces as a 'high-level' visual property, and suggest instead that forces are recovered early, and can even shape our perception of seemingly lower-level features of how an object is seen to be moving.

In the four experiments reported below, we found evidence for just this sort of influence. Observers were consistently more sensitive to changes in objects' speeds when these changes were seen as resisting the force of gravity, and less sensitive to changes in objects' speeds when these changes were seen as being due to the operation of gravity.

## Experiment 1a: Acceleration Detection

In an initial experiment, observers viewed animations featuring single moving objects, which either sped up, or stayed moving at the same speed throughout the animation. After each animation, observers reported whether the object accelerated, or remained at a constant speed (see Figure 1). We predicted that observers would be more sensitive to the acceleration of upward-moving objects (i.e. when the object's acceleration would need to resist the force of gravity) compared to downward-moving objects (i.e. when the object's acceleration could be readily attributed to the force of gravity).

### Method

All research procedures were approved by the Institutional Review Board at [university name redacted for double blind peer review]. The experimental design and analyses were preregistered at https://osf.io/hdfns/. Example displays from all conditions may be viewed at https://www.nssrperception.com/projects.html.

*Observers*: Fifty observers (16 female, 32 male, 2 nonbinary; average age=25.20 years) with normal or corrected-to-normal acuity were recruited through the online labor market Prolific (https://prolific.co/), which is often use for studies of this sort. For a discussion of this subject pool's reliability, see Palan & Schitter (2018). During data collection seven participants were excluded and replaced (five who failed to provide complete data and two who at the end of the study rated their attention as less than 70 on a scale from 0-100). Each participated in a 10-min online session on the experiment hosting site Pavlovia (https://pavlovia.org/), in return for a small monetary payment. The sample size was based on a power analysis run on pilot data.

*Stimuli*: Stimuli were created using custom software written using the PsychoPy libraries (Peirce, 2007). On each trial, the display featured a horizontally centered black [#000000] disc moving vertically on a light gray [#C0C0C0] background. On Upward-moving trials, the disc was initialized at a randomized vertical position between 380 and 420 pixels below the screen's center. On Downward-moving trials, the disc was initialized at a randomized vertical position between 380 and 420 pixels above the screen's center.

In both the Upward-moving and Downward-moving conditions, on half of the trials, the disc sped up: it moved at 180 pixels per second for the first 200 pixels of its trajectory, accelerated at a rate of 2.4 pixels per second$^2$ until it reached a speed of 300 pixels per second, and then remained at a constant speed of 300 pixels per second for the remaining 350 pixels of its trajectory.  On the other half of trials, the disc moved at a constant speed throughout the animation: either at 180 pixels per second (on half of the constant speed trials) or at 300 pixels per second (on the other half).

*Procedure*: Each trial was preceded by a 1-second blank inter-trial interval, and was immediately followed by a response screen which prompted the observer to press one of two keys to report whether the disc had sped up.  The next trial began as soon as a response was made.

The experiment had a 2 (Upward vs. Downward) x 2 (Speed-up vs. Constant) within-subjects design.  Observers completed eight practice trials (two of each condition in a randomized order) — the results of which were not recorded.  They then completed 64 experimental trials, with the conditions again counterbalanced and presented in a randomized order.  After the practice and halfway through the experimental trials, they saw a screen prompting them to take a short break.

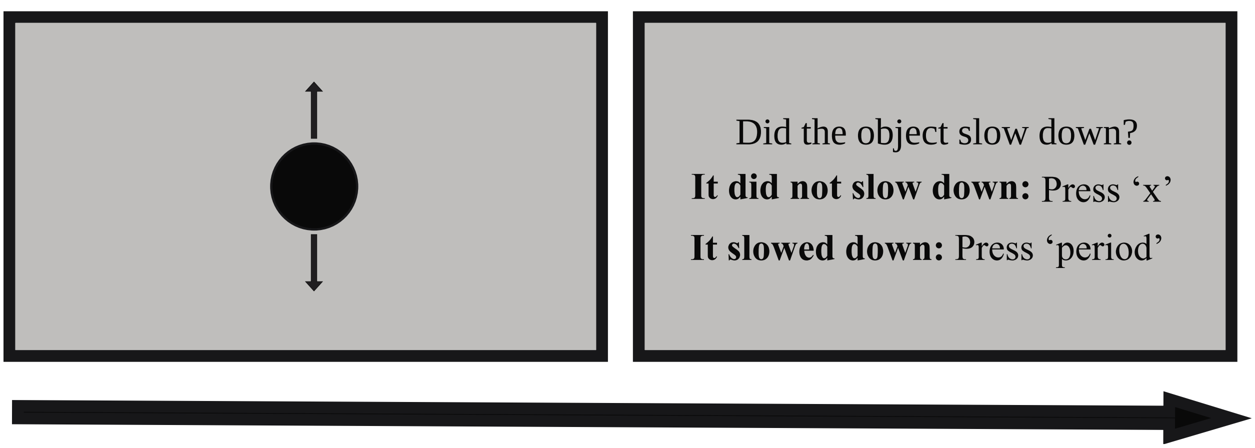


*Figure 1*: Depiction of the displays used in the Acceleration Detection Experiments.  On each trial, observers viewed an animation in which a disc moved either upward or downward. Afterward, they pressed a key to report whether the disc sped up, or remained moving at a constant speed.

**Results**

We categorized each response as a hit, miss, false alarm, or correct rejection, and computed d′ (a measure of sensitivity, as distinct from response bias) for the Upward and Downward conditions (Green & Swets, 1966).  As depicted in Figure 2, observers were more sensitive to whether or not the object sped up on Upward trials (d′=2.28) compared to Downward trials (d′=1.96), $t(49)=3.95$, $p<0.001$, $d_z=0.56$ — an effect that was driven by higher hit rates in the Upward condition (HR=0.78) than in the Downward condition (HR=0.67), $t(49)=4.39$, $p<0.001$, $d_z=0.62$. There was no significant difference in false alarm rate between the Upward (FA=0.12) and Downward (FA=0.11) conditions, $t(49)=1.16$, $p=0.252$, $d_z=0.16$. A comparison of response criterion (β) between Upward and Downward trials revealed that observers had a lower threshold to report a speed-up when the object moved Upward (β=2.26) than when it moved Downward (β=3.01), $t(49)=2.60$, $p=0.012$, $d_z=0.34$.

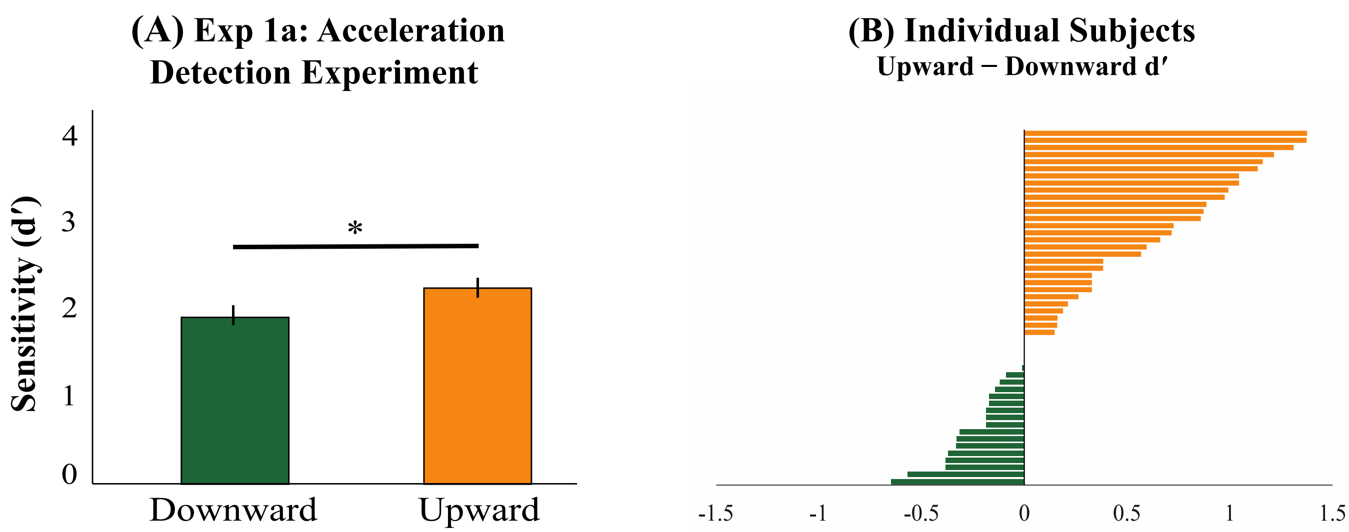


*Figure 2*: (A) Sensitivity (d' values) for the Downward and Upward conditions in Experiment 1a. Error bars reflect 95% confidence intervals, subtracting out the shared variance. (B) Sensitivity difference scores (Upward – Downward) for individual observers in Experiment 1a.

## Experiment 1b: Direct Replication

Given the importance of direct replications, we next reran the experiment on a new sample of 50 subjects (22 female, 28 male; average age=24.72 years). During data collection five participants were excluded and replaced (two who failed to provide complete data and three who at the end of the study rated their attention as less than 70 on a scale from 0-100).

As depicted in Figure 3, observers were again more sensitive to whether or not an object sped up on Upward trials (d′=2.47) compared to Downward trials (d′=2.20), $t(49)=3.28$, $p=0.002$,

$d_z$=0.46 — an effect that was again driven by higher hit rates in the Upward condition (HR=0.80) than in the Downward condition (HR=0.70), $t(49)=5.01$, $p<0.001$, $d_z$=0.71. There was a small, marginally significant difference in false alarm rate between the Upward (FA=0.07) and Downward (FA=0.06) conditions, $t(49)=1.73$, $p=0.089$, $d_z$=0.25. A comparison of response criterion between Upward and Downward trials revealed that observers had a lower threshold to report a speed-up when the object moved Upward (β=2.22) than when it moved Downward (β=3.16), $t(49)=4.14$, $p<0.001$, $d_z$=0.58.

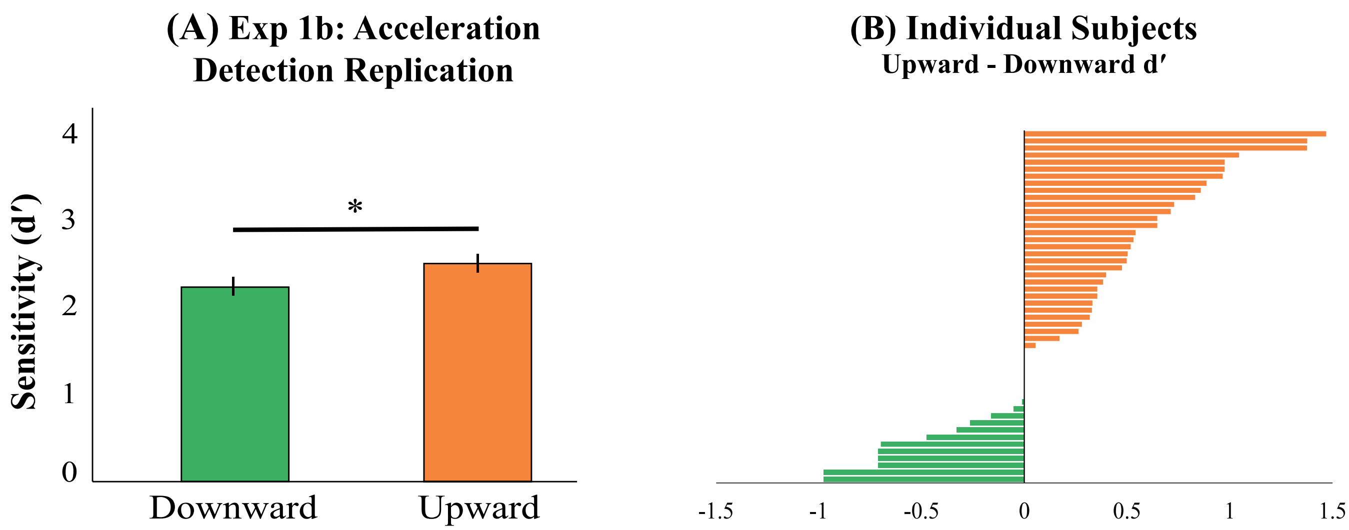


*Figure 3*: (A) Sensitivity (d' values) for the Downward and Upward conditions in Experiment 1b. Error bars reflect 95% confidence intervals, subtracting out the shared variance. (B) Sensitivity difference scores (Upward – Downward) for individual observers in Experiment 1b.

## <u>Discussion</u>

Observers were better at detecting speed-ups for Upward-moving objects than for Downward-moving objects. These results indicate that we are more sensitive to an object's acceleration when it is opposed to the force of gravity, compared to the same acceleration when it appears caused by the force of gravity.

## Experiment 2a: Deceleration Detection

The hypothesis that observers are more sensitive to speed changes that appear to resist gravity makes the *opposite* prediction for the detection of deceleration. If an upward-moving object slows down, then this slow-down is attributable to the force of gravity, and observers should be relatively insensitive to this. By contrast, if a downward-moving object slows down, then this slow-down may be attributed to a 'braking' force resisting gravity, in which case observers should be more sensitive to this. To test this prediction, we next ran a Deceleration Detection Experiment, which was analogous to the Acceleration Detection Experiments, except that now observers were instead tasked with detecting slow-downs.

### Method

Experiment 2a was identical to Experiments 1a and 1b, except as noted here.

*Observers*: Fifty observers (25 female, 25 male; average age=26.00 years) participated. During data collection eight participants were excluded and replaced (five who failed to provide complete data and three who at the end of the study rated their attention as less than 70 on a scale from 0-100).

*Stimuli*: In both the Upward-moving and Downward-moving conditions, on half of trials, the disc slowed down: it moved at 300 pixels per second for the first 200 pixels of its trajectory, decelerated at a rate of 2.4 pixels per second$^2$ until it reached a speed of 180 pixels per second, and then remained at a constant speed of 180 pixels per second for the remaining 350 pixels of its trajectory. On the other half of trials, the disc moved at a constant speed throughout: either at 180 pixels per second (on half of the constant speed trials) or at 300 pixels per second (on the other half).

### Results

We categorized each response as a hit, miss, false alarm, or correct rejection, and computed d′ for the Upward and Downward conditions. As depicted in Figure 4, observers were more sensitive to whether or not an object slowed down on Downward trials (d′=2.93) compared to Upward trials (d′=2.44), $t(49)=5.24$, $p<0.001$, $d_z=0.74$ — an effect that was driven by higher hit rates in the Downward condition (HR=0.90) than in the Upward condition (HR=0.76), $t(49)=6.17$, $p<0.001$, $d_z=0.87$. There was no difference in false alarm rate between Downward (FA=0.08) and Upward (FA=0.08) trials, $t(49)=0.32$, $p=0.749$, $d_z=0.05$. A comparison of response criterion between Downward and Upward trials revealed that observers had a lower threshold to report a slow-down when the object moved Downward (β=1.41) than when it moved Upward (β=2.62), $t(49)=5.01$, $p<0.001$, $d_z=0.71$.

Observers' pattern of sensitivity across the Upward and Downward conditions in this experiment was qualitatively opposite to the pattern of sensitivity across the Upward and Downward conditions in the Acceleration Detection Experiments. To confirm this, we computed the Upward − Downward sensitivity differences for observers in this experiment, and ran between-subjects tests to compare these to the same difference scores computed for the observers in Experiments 1a and 1b. The difference scores in the present experiment were significantly different from those of both Experiment 1a (-0.49 vs. 0.32, $t(98)=6.55$, $p<0.001$, $d=0.62$), and Experiment 1b (-0.49 vs. 0.27, $t(98)=6.09$, $p<0.001$, $d=0.63$).

Similar to sensitivity, observers' pattern of hit rates across the Upward and Downward conditions in this experiment was qualitatively opposite to the pattern of hit rates across the Upward and Downward conditions in the Acceleration Detection Experiments. To confirm this, we computed the Upward − Downward hit rate differences for observers in this experiment, and ran between-subjects tests to compare these to the same difference scores computed for the observers in Experiments 1a and 1b. The hit rate difference scores in the present experiment were significantly different from those of both Experiment 1a (-0.14 vs 0.11, $t(98)=7.38$, $p<0.001$, $d=0.17$), and Experiment 1b (-0.14 vs 0.11, $t(98)=7.93$, $p<0.001$, $d=0.16$).

In contrast, observers' pattern of false alarm rates across the Upward and Downward conditions in this experiment was nonsystematic and qualitatively similar to the pattern of false alarm rates across the Upward and Downward conditions in the Acceleration Detection Experiments. To confirm this, we computed the Upward − Downward false alarm differences for observers in this experiment, and ran between-subjects tests to compare these to the same difference scores computed for the observers in Experiments 1a and 1b. The false alarm rate difference scores in the present experiment did not differ from those of either Experiment 1a (0.00 vs 0.02, $t(98)=1.08$, $p=0.284$, $d=0.09$), or Experiment 1b (0.00 vs 0.02, $t(98)=1.29$, $p=0.199$, $d=0.07$).

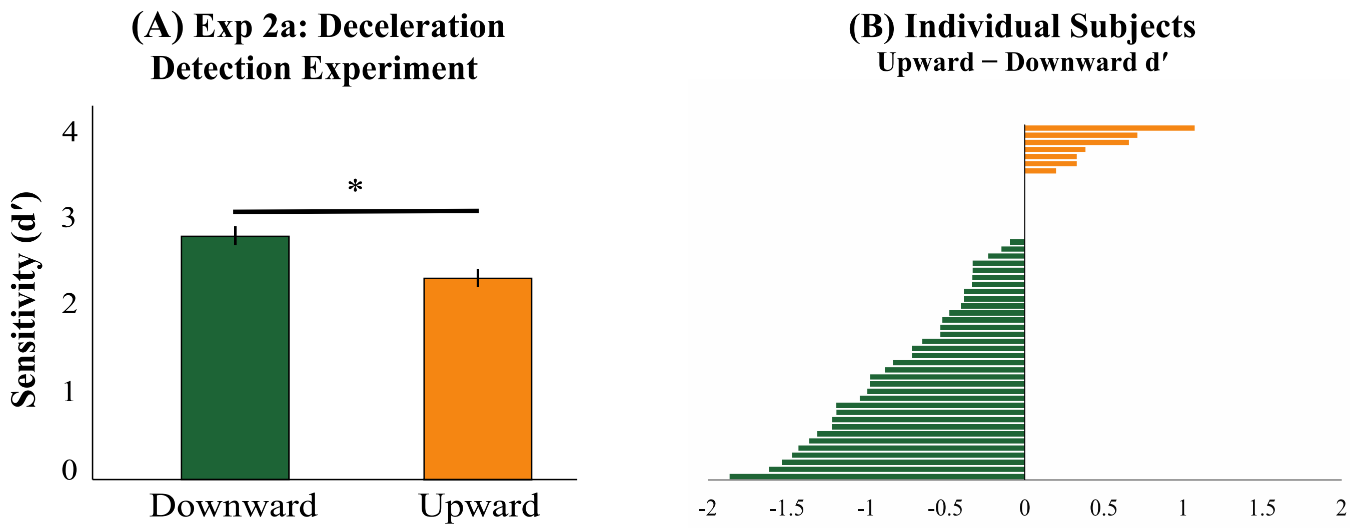


*Figure 4*: (A) Sensitivity (d' values) for the Downward and Upward conditions in Experiment 2a. Error bars reflect 95% confidence intervals, subtracting out the shared variance. (B) Sensitivity difference scores (Upward – Downward) for individual observers in Experiment 2a.

**Experiment 2b: Direct Replication**

We next directly replicated the Deceleration Detection Experiment on a new sample of 50 subjects (15 female, 34 male, 1 nonbinary; average age=25.26 years). During data collection five participants were excluded and replaced (two who failed to provide complete data and three who at the end of the study rated their attention as less than 70 on a scale from 0-100).

The the results of this replication are depicted in Figure 5. Observers were again more sensitive to slow-downs on Downward trials (d′=2.93) compared to Upward trials (d′=2.50), $t(49)=4.74$, $p<0.001$, $d_z=0.67$ — an effect that was again driven by higher hit rates in the Downward condition (HR=0.91) than in the Upward condition (HR=0.78), $t(49)=5.86$, $p<0.001$, $d_z=0.82$. This time there was a significant difference in false alarm rate between Downward (FA=0.07) and Upward (FA=0.05) trials, $t(49)=2.53$, $p=0.015$, $d_z=0.36$. A comparison of response criterion between Downward and Upward trials revealed that observers had a lower threshold to report a slow-down when the object moved Downward (β=1.47) than when it moved Upward (β=2.79), $t(49)=5.98$, $p<0.001$, $d_z=0.85$.

Observers' pattern of sensitivity across the Upward and Downward conditions in this experiment was qualitatively opposite to the pattern of sensitivity across the Upward and Downward conditions in the Acceleration Detection Experiments. To confirm this, we computed the Upward − Downward sensitivity differences for observers in this experiment, and compared these to the same difference scores computed for the observers in Experiments 1a and 1b. The difference scores in the present experiment were significantly different from those of both Experiment 1a (-0.44 vs. 0.32, $t(98)=6.17$, $p<0.001$, $d=0.61$), and Experiment 1b (-0.44 vs. 0.27, $t(98)=5.72$, $p<0.001$, $d=0.62$).

Similar to sensitivity, observers' pattern of hit rates across the Upward and Downward conditions in this experiment was qualitatively opposite to the pattern of hit rates across the Upward and Downward conditions in the Acceleration Detection Experiments. To confirm this, we computed the Upward − Downward hit rate differences for observers in this experiment, and ran between-subjects tests to compare these to the same difference scores computed for the observers in Experiments 1a and 1b. The hit rate difference scores in the present experiment were significantly different from those of both Experiment 1a (-0.13 vs 0.11, $t(98)=7.13$, $p<0.001$, $d=0.17$), and Experiment 1b (-0.13 vs 0.11, $t(98)=7.69$, $p<0.001$, $d=0.15$).

This time, observers' pattern of false alarm rates across the Upward and Downward conditions differed from the pattern of false alarm rates across the Upward and Downward conditions in the Acceleration Detection Experiments. To confirm this, we computed the Upward − Downward false alarm differences for observers in this experiment, and ran between-subjects tests to compare these to the same difference scores computed for the observers in Experiments 1a and 1b. The false alarm rate difference scores in the present experiment were significantly different from those of both Experiment 1a (-0.02 vs 0.02, $t(98)=2.27$, $p=0.026$, $d=0.07$), and Experiment 1b (-0.02 vs 0.02, $t(98)=2.96$, $p=0.004$, $d=0.06$).

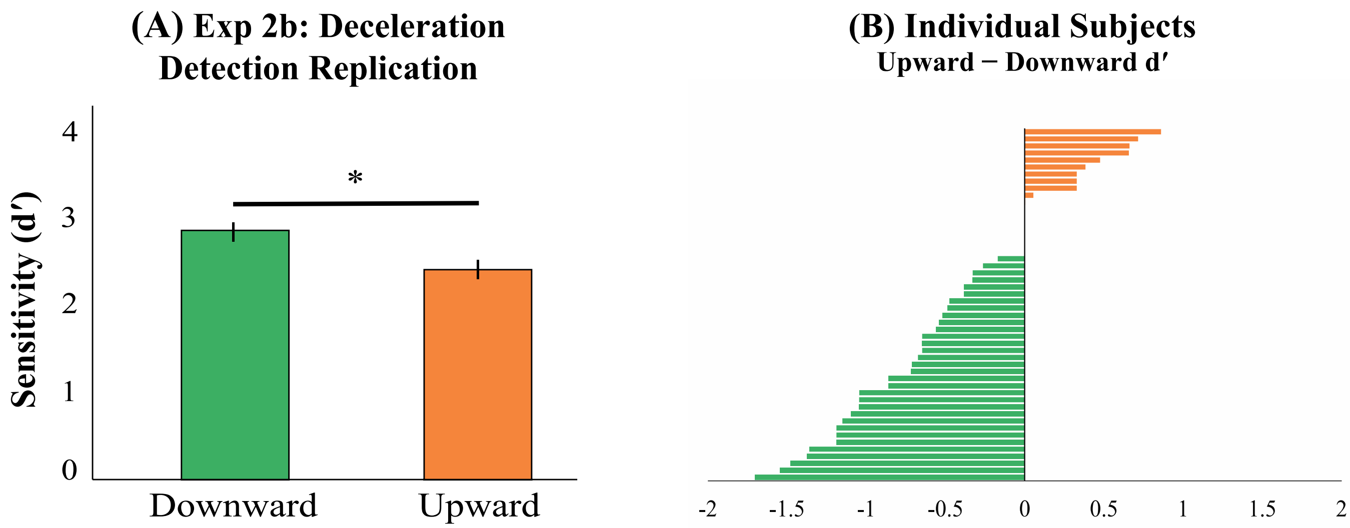


*Figure 5*: (A) Sensitivity (d' values) for the Downward and Upward conditions in Experiment 2b. Error bars reflect 95% confidence intervals, subtracting out the shared variance. (B) Sensitivity difference scores (Upward – Downward) for individual observers in Experiment 2b.

**<u>Discussion</u>**

Observers were better at detecting slow-downs for Downward-moving objects than for Upward-moving objects. These results indicate that we are more sensitive to an object's deceleration when it is opposed to the force of gravity, compared to the same deceleration when it appears caused by the force of gravity.

## General Discussion

The four experiments reported here all support a clear conclusion: When viewing a moving object, observers are more sensitive to a change in that object's speed if that change is contrary to natural gravitational acceleration. In Experiments 1a and 1b, speed-ups were more readily detected for upwardly moving objects than for downwardly moving objects. In Experiments 2a and 2b, slow-downs were more readily detected for downwardly moving objects than for upwardly moving objects. These patterns were highly replicable, and they were observed under exceedingly well controlled conditions, with the *same exact speed changes* detected differentially well depending on how they were oriented. This orientation-dependence appears to reflect a fundamental limit on visual processing of acceleration and deceleration, as it emerged even when observers were trying their best to detect the speed changes in all conditions, and even using stripped-down displays that bore little resemblance to natural scenes. However, future research should consider whether these effects generalize to more naturalistic viewing conditions, for example by using virtual reality displays.

**Prioritization of animacy in visual cognition**

The current results are consistent with past research, which has found that animate-looking stimuli are prioritized in visual attention and memory. When viewing static images, observers pay more attention to people and animals than to plants or vehicles (Calvillo & Hawkins, 2016; New et al., 2007; New et al., 2010). Alongside shape and texture cues (Banno & Saiki, 2015; Levin et al., 2001; Long et al., 2017), motion also acts as a powerful cue to animacy, particularly when it leads to the impression of *self-propelledness* (Gelman et al., 1995; Leslie, 1994; Schultz & Bülthoff, 2013). For example, moving objects look more alive when they undergo large, apparently self-propelled, heading changes — but not when 'paddles' are added to the display, which cause these same heading changes to appear as inanimate bouncing (Tremoulet & Feldman, 2000/2006). And, of particular relevance to the present studies, objects also appear more alive if they move upward (as if resisting gravity) compared to downward (as if their movement is caused by gravity; Szego & Rutherford, 2008). Like static visual cues to animacy, self-propelledness captures attention, such that observers are more sensitive to the disappearance of an object immediately after it makes a self-propelled-looking heading change (Pratt et al., 2010). The present results, wherein observers were more sensitive to accelerations and decelerations contrary to natural gravitational acceleration, may be understood as an instance of the more general prioritization of animacy within visual cognition and memory (see also Bonin et al., 2014; Meinhardt et al., 2020; Nairne et al., 2013/2017; van Buren & Scholl, 2017).

**Physical forces in perception, memory, and reasoning**

Beyond the perception of self-propelledness, there have been several investigations of how physical forces influence how we perceive, remember, and reason about visual stimuli. On the perceptual side, recent work suggests that observers are better at tracking a set of moving objects amid distractors when the objects in the display collide with one another in physically realistic ways (Lau & Brady, 2020). Visual memory also shows biases that are consistent with physical regularities, as in the well known phenomenon of 'representational momentum'. In these experiments, observers view displays containing a single moving object, which abruptly disappears. When reporting the last visible position of the object, they misremember it as displaced in the direction it had been moving — suggesting that we remember objects in a way that attributes to them the physical property of *momentum* (for reviews, see Hubbard 2005, 2014). Memory displacements are larger for downwardly moving objects than for upwardly moving objects, suggesting that memory also encodes an implicit model of the force of *gravity* (Hubbard & Bharucha, 1988; for a review see Hubbard, 2020). In further support of this, downward displacements in memory — termed 'representational gravity' — have also been observed for laterally moving objects (Hubbard, 1990; Hubbard & Bharucha, 1988), and for images of static objects that are physically unsupported, and so likely to fall, (such as a houseplant floating in midair; Bertamini 1993; Freyd et al. 1988; Hubbard & Ruppel, 2000). Subsequent research has found that representational gravity is based on the integration of signals from several sensory modalities, including visual cues, vestibular cues, and somatosensory cues to the orientation of one's own body axis (De Sá Teixeira & Hecht, 2014; De Sá Teixeira et al., 2017; Indovina et al., 2005). Although representational gravity approximates how real objects behave under natural gravity, it has also been found to deviate from natural gravity in some interesting ways. For example, in representational gravity, larger objects undergo greater downward displacements than smaller ones — whereas in natural gravity, larger objects do not accelerate downward more quickly than smaller ones (De Sá Teixeira & Oliveira, 2014; Hubbard, 1997; Hubbard, 1998).

In addition to these demonstrations of *implicit* knowledge of physics in the operation of attention and memory, there have also been several studies exploring how subjects *explicitly reason* about physical structures and events. When asked whether an object or structure will remain balanced or fall over, observers make judgments that are approximately accurate (Barnett-Cowan et al., 2011; Battaglia et al., 2013; Lupo & Barnett-Cowan, 2015). Moreover, when viewing dynamic point light displays, observers are able to correctly estimate the weight of a lifted object based on dynamic cues (Runeson & Frykholm, 1981; Valenti & Costall, 1997). Although observers are fairly competent at explicit physical reasoning during online perception of visual displays, they do worse when they are asked to imagine physical events. For example, work on "intuitive physics" has found that naive subjects often falsely predict that an object dropped from a moving airplane will fall directly downward (rather than at an angle; McCloskey et al., 1983; for a review, see Kubricht et al., 2017).

In summary, previous investigations have explored both observers' implicit knowledge of physics (as revealed through biases in attention and memory performance), as well as their explicit knowledge of physics (as revealed through the overt judgments that they make about physical objects and events). The present results are firmly in the first category, as observers were not asked to reason about what objects *should* do under natural physics, but rather were instructed to do their best to detect *all* speed changes. This revealed a striking, and seemingly irresistible, bias in visual sensitivity, such that observers were better able to notice accelerations and decelerations when they were opposite the direction of natural gravitational acceleration.

### ***Seeing*** **physical forces: Functional interactions with the processing of "low level" features**

The present results contribute to a growing list of cases in which the processing of a canonically 'lower-level' visual feature operates in a way that integrates seemingly 'higher-level' information. For example, one might naively hold the view that first, objects' motions are perceived, and following this, causal relationships are inferred. However, recent work has turned this view on its head, suggesting that the perception of causality both arises from, and also reciprocally influences, the perception of objects' spatiotemporal relationships (e.g. Bechlivanidis & Lagnado, 2016; Chen & Yan, 2020; Meyerhoff & Scholl, 2018; Scholl & Nakayama, 2004).

From the present experiments, we conclude that the perception of self-propelledness shows evidence of this same reciprocity: not only do objects' speed changes produce vivid impressions that they are alive and self-propelled, and the reverse *also* occurs, such that a speed change that looks like it is resisting the force of gravity is more likely to be noticed in the first place. Thus, the perception of the physical forces acting on and within objects is not merely an 'endpoint' of visual processing, but rather plays a far richer role in determining the perception of other, seemingly lower-level, properties of how objects move.

## Acknowledgements

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