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May the Force Be Against You: Better Visual Sensitivity to Speed Changes Opposite to Gravity

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Beyond seemingly lower-level features such as color and motion, visual perception also recovers properties more commonly associated with higher-level thought, as when an upwardly accelerating object is seen not just as moving, but moreover as self-propelled, and resisting the force of gravity. Given past research demonstrating the prioritization of living things in attention and memory, here we hypothesized that observers would be more sensitive to an object's speed changes if those speed changes were opposite to natural gravitational acceleration. Across six experiments, we found that observers were more sensitive to objects' accelerations when they moved upward (when those accelerations were opposite to gravity) and less sensitive to their accelerations when they moved downward (when those accelerations were consistent with gravity). Moreover, observers were more sensitive to objects' decelerations when they moved downward (when those decelerations appeared as "braking" against gravity), and less sensitive to their decelerations when they moved upward (when those decelerations were consistent with gravity). This greater visual sensitivity to speed changes opposite to gravity is consistent with previous results suggesting that we readily monitor the world for cues to animacy.

Public Significance Statement
When an object changes speed, what causes you to notice this? In several experiments, observers were better at noticing a change in an object's speed when it accelerated opposite to natural gravitational acceleration. Greater sensitivity to speed changes opposite gravity may help us to detect the movements of living things.

Keywords: perception of forces, perception of self-propelledness, perception of animacy, perception of causality, perception of gravity,

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 (Runeson & Frykholm, 1983; 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 & Baillargeon, 2005), and even in nonhuman animals such as chickens (e.g., Di Giorgio et al., 2021).

By far, the most consistent force in our environment is gravity. Objects have a strong tendency to accelerate downward (Aristotle, 4th Century BCE; Newton, 1687). Because of this, when an object accelerates *opposite* to gravity, this indicates an internal force—which is in turn a cue to animacy (Bingham et al., 1995; Frankenhuis & Barrett, 2013; Gelman et al., 1995; Tremoulet & Feldman, 2000). Does the appearance of a speed change as self-propelled determine whether we notice it in the first place? In the present research, given past work demonstrating the prioritization of animate stimuli in attention and memory (the *animate monitoring hypothesis*; Nairne et al., 2013; New et al., 2007; van Buren & Scholl, 2017), we reasoned that when observers must detect whether or not an object has changed speed, they might be particularly efficient at detecting speed changes opposite to gravity.

Gravitational Expectations in Visuomotor Responses

When observers view a moving object, and are asked to predict when it will reach a prespecified location (e.g., by pressing a key, or by reaching out to intercept it), they are much more accurate when that object shows the typical pattern of downward acceleration

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(McIntyre et al., 2001; Zago et al., 2004, 2005, 2008, 2010, 2011): If the object moves downward at a constant speed, observers react too early (they predict acceleration), and if the object moves upward at a constant speed, they react too late (they predict deceleration), and similar expectations of downward acceleration are made when intercepting parabolic trajectories (Bosco et al., 2012; de la Malla & López-Moliner, 2015; Delle Monache et al., 2014; Diaz et al., 2013; Gómez & López-Moliner, 2013; Lacquaniti et al., 2015). In fact, this visuomotor expectation of downward acceleration is so strong that it persists even when gravity is absent. In a particularly dramatic demonstration, astronauts in 0*g* were asked to intercept moving objects launched from either the ceiling or floor of their spaceship. Even after 15 days in space without seeing gravity-consistent movements, their reaching times continued to betray an assumption that downwardly-moving objects accelerate, and upwardly-moving objects decelerate (McIntyre et al., 2001; see also Jörges & López-Moliner, 2017).

The Present Research: Does Visual Detection Prioritize Speed Changes Opposite to Gravity?

When reaching out to grab a moving object, it makes sense to assume that it will accelerate downward, to aid accurate timing of one's reach. However, when it comes to *detecting* whether a speed change is occurring, visual processing may prioritize not what is typical in the environment, but rather what *matters* most. In particular, according to the *animate monitoring hypothesis*, we should be more sensitive to speed changes opposite to gravity, because these speed changes signal the presence of something alive and self-propelled. Here we used a signal detection task to test whether the orientation of a speed change relative to gravity determines whether it is detected in the first place. Observers viewed moving objects, and detected whether or not they changed speed. Across the six experiments reported below, we found that observers were consistently more sensitive to changes in objects' speeds when these changes opposed natural gravitational acceleration, and less sensitive to changes in objects' speeds when these changes were consistent with the operation of gravity.

Experiment 1a: Acceleration Detection (Upward vs. Downward)

In an initial experiment, observers viewed animations featuring single moving objects, which either accelerated, or stayed moving at the same speed throughout the animation. After each animation, observers reported whether the object accelerated or remained moving at a constant speed. We predicted that observers would be more sensitive to the acceleration of upward-moving objects (i.e., when the speed change was opposite to gravity) compared with downward-moving objects (i.e., when the speed change was consistent with gravity).

Method

All research procedures were approved by the Human Research Protection Program at The New School. The experimental design and analyses were preregistered at https://osf.io/pme3k/. Example displays from all conditions may be viewed at https://www.nssrperception.com/project-speed-changes-opposite-gravity.html.

Observers

Fifty observers (16 female, 32 male, two nonbinary; average age = 25.20 years, *SD* = 4.94) with normal or corrected-to-normal acuity were recruited through the online labor market Prolific (https://prolific.co/), which is often used for studies of this sort. For a discussion of this subject pool's reliability, see Palan & Schitter (2018). Each observer participated in a 10-min online session on the experiment hosting site Pavlovia (https://pavlovia.org/), in return for a small monetary payment. 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 to 100). The sample size was determined as follows: In a pilot experiment, a paired *t*-test revealed greater sensitivity to acceleration in Upward versus Downward trials, with an effect size of $d_z = 0.52$. A power analysis conducted using R's pwr library (Champely, 2020) indicated that we would need at least 43 subjects to detect this effect with 80% power at an α level of 0.05. We preregistered a sample size of 50 just to be safe.

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 (see Figure 1). 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 accelerated: it moved at a constant speed of 180 pix/s for 1.10 s, then accelerated at a rate of 144 pix/s^2 for 0.83 s, then moved at a constant speed of 300 pix/s for 1.33 s[1] On the other half of the trials, the disc moved at a constant speed for the whole distance: either at 180 pix/s (on half of the constant speed trials) or at 300 pix/s (on the other half).

Procedure

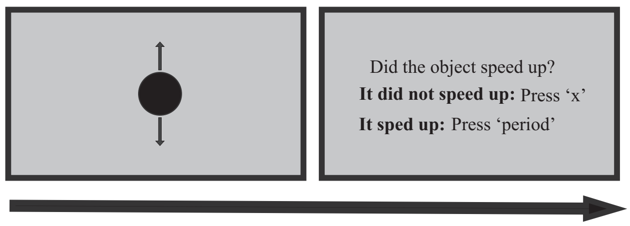
Each trial was preceded by a 1-s blank inter-trial interval, and was immediately followed by a response screen which prompted the observer to press one of two keys to report whether the disc had accelerated. The next trial began as soon as a response was made.

The experiment had a 2 (Upward vs. Downward) × 2 (Acceleration 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

[1] During piloting, we selected an acceleration rate which produced intermediate detection performance, to avoid a floor or a ceiling effect. For most of our online subjects, 144 pix/s² would have appeared slower than 1*g* downward acceleration in a vacuum, and allowing for differences due to differences in at-home monitor sizes, closer to the acceleration of a skier descending a ski slope.

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 Accelerated, or Remained Moving at a Constant Speed



halfway through the experimental trials, they saw a screen prompting them to take a short break.

Transparency and Openness

All study designs and analyses were preregistered on the Open Science Framework and can be accessed at https://osf.io/hdfns/. All data are publicly available and can be accessed at https://osf.io/pme3k/. Data were collected from 2021 to 2022.

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 2a, observers were more sensitive to whether or not the object accelerated on Upward trials ($d' = 2.28$) compared with Downward trials ($d' = 1.96$), $t(49) = 3.95$, $p < .001$, $d_z = 0.56$—an effect that was driven by higher hit rates in the Upward condition ($HR = 0.78$) than in the Downward condition ($HR = 0.67$), $t(49) = 4.39$, $p < .001$, $d_z = 0.62$. There was no significant difference in false alarm rate between the Upward ($FA = 0.12$) and Downward ($FA = 0.11$) conditions, $t(49) = 1.16$, $p = .252$, $d_z = 0.16$. A comparison of response criterion (β) between Upward and Downward trials revealed that observers had a lower threshold to report acceleration when the object moved Upward ($\beta = 2.26$) than when it moved Downward ($\beta = 3.01$), $t(49) = 2.60$, $p = .012$, $d_z = 0.34$.

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, $SD = 3.48$). 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 to 100).

As depicted in Figure 2b, observers were again more sensitive to whether or not an object accelerated on Upward trials ($d' = 2.47$) compared with Downward trials ($d' = 2.20$), $t(49) = 3.28$, $p = .002$, $d_z = 0.46$—an effect that was again driven by higher hit rates in the Upward condition ($HR = 0.80$) than in the Downward condition ($HR = 0.70$), $t(49) = 5.01$, $p < .001$, $d_z = 0.71$. There was no difference in false alarm rate between the Upward ($FA = 0.07$) and Downward ($FA = 0.06$) conditions, $t(49) = 1.73$, $p = .089$, $d_z = 0.25$. A comparison of response criterion between Upward and Downward trials revealed that observers had a lower threshold to report acceleration when the object moved Upward ($\beta = 2.22$) than when it moved Downward ($\beta = 3.16$), $t(49) = 4.14$, $p < .001$, $d_z = 0.58$.

Discussion

In both the original experiment and the direct replication, observers were better at detecting acceleration 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 opposite to the force of gravity, compared with the same acceleration when it is consistent with the force of gravity.

Experiment 2a: Acceleration Detection (Upward vs. Horizontal)

These results suggest that observers are more sensitive to acceleration opposite to gravity, consistent with the *animate monitoring hypothesis*. However, it remains possible that there is no advantage for detecting acceleration opposite to gravity, and that observers are simply *less* sensitive to acceleration that is *consistent* with gravity. To determine whether the previous effect was driven by an advantage for detecting acceleration opposite to gravity, in Experiment 2 we compared acceleration detection in an Upward moving condition (which was identical to the Upward moving condition in the previous experiment) to acceleration detection in a new Horizontally moving baseline condition. Here, better detection performance in the Upward relative to the Horizontal condition would support the hypothesis that we are more sensitive to acceleration opposite to gravity.

Method

Experiment 2 was identical to Experiment 1, except as noted here.

Observers

One-hundred observers (65 female, 35 male; average age = 24.35 years, $SD = 3.92$) 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 to 100). The sample size was determined as follows: In a pilot experiment, a paired *t*-test revealed greater sensitivity to acceleration in Upward versus Horizontal trials, with an effect size of $d_z = 0.32$. A power analysis conducted using R's pwr library (Champely, 2020) indicated that we would need at least 84 subjects to detect this effect with 80% power at an α level of 0.05. We preregistered a sample size of 100 just to be safe.

Procedure

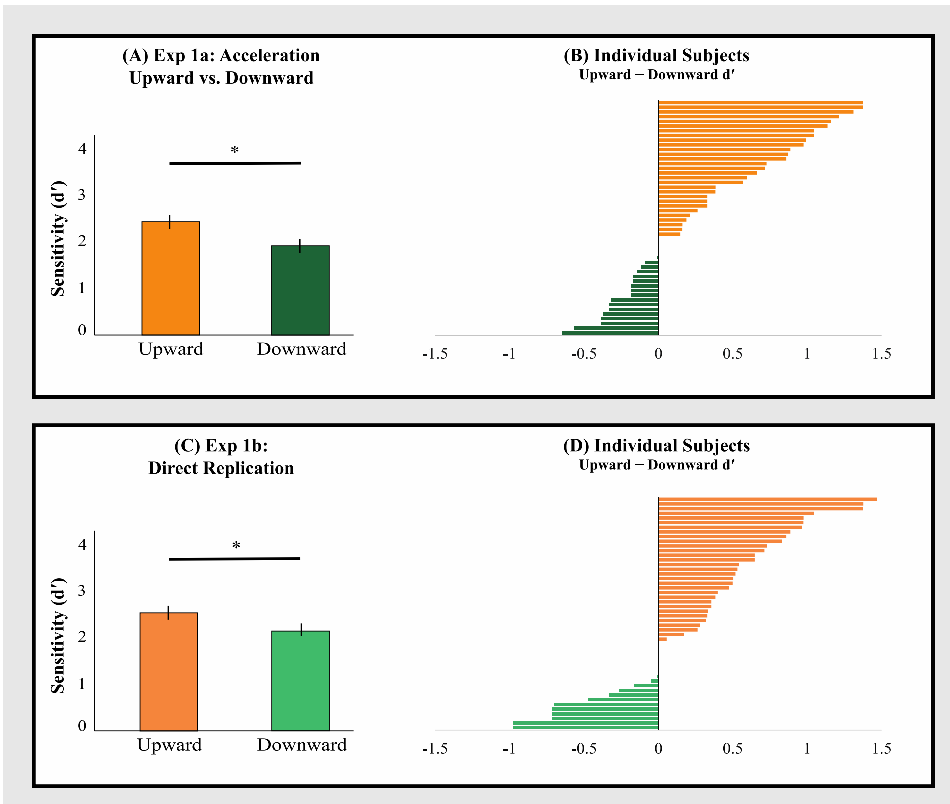
Observers again detected acceleration. The disc moved Upward on half of the trials and Horizontally on the other half. For half of the observers, Horizontal trials featured leftward movement and, for the other half, these trials featured rightward movement (but this did not have any effect on the results).

Stimuli

In both the Upward-moving and Horizontally-moving conditions, on half of the trials, the disc accelerated: it moved at 180 pix/s for 1.10 s, then accelerated at a rate of 144 pix/s^2 for 0.83 s, then

Figure 2

(A) Sensitivity (d′ Values) for the Upward and Downward Conditions in Experiment 1a. (B) Sensitivity Difference Scores (Upward – Downward) for Individual Observers in Experiment 1a. (C) Sensitivity for the Upward and Downward Conditions in Experiment 1b. (D) Sensitivity Difference Scores (Upward – Downward) for Individual Observers in Experiment 1b. Error bars reflect 95% confidence intervals, subtracting out the shared variance



Note. See the online article for the color version of this figure.

moved at a constant speed of 300 pix/s for 1.33 s. On the other half of the trials, the disc moved at a constant speed throughout the animation: either at 180 pix/s (on half of the constant speed trials) or at 300 pix/s (on the other half).

Results

We computed d′ for the Upward and Horizontal conditions. As depicted in Figure 3, observers were more sensitive to whether or not the object accelerated on Upward trials (d′ = 2.57) compared with Horizontal trials (d′ = 2.37), $t(99) = 3.54$, $p < .001$, $d_z = 0.35$—an effect that was driven by higher hit rates in the Upward condition (HR = 0.81) than in the Horizontal condition (HR = 0.76), $t(99) = 3.34$, $p < .001$, $d_z = 0.33$. There was no difference in false alarm rate between the Upward (FA = 0.07) and Horizontal (FA = 0.07) conditions, $t(99) = 0.36$, $p = .719$, $d_z = 0.04$. A comparison of response criterion between Upward and Horizontal trials revealed that observers had a lower threshold to report acceleration when the object moved Upward ($\beta = 2.28$) than when it moved Horizontally ($\beta = 2.78$), $t(99) = 3.17$, $p = .002$, $d_z = 0.32$.

Experiment 2b: Direct Replication

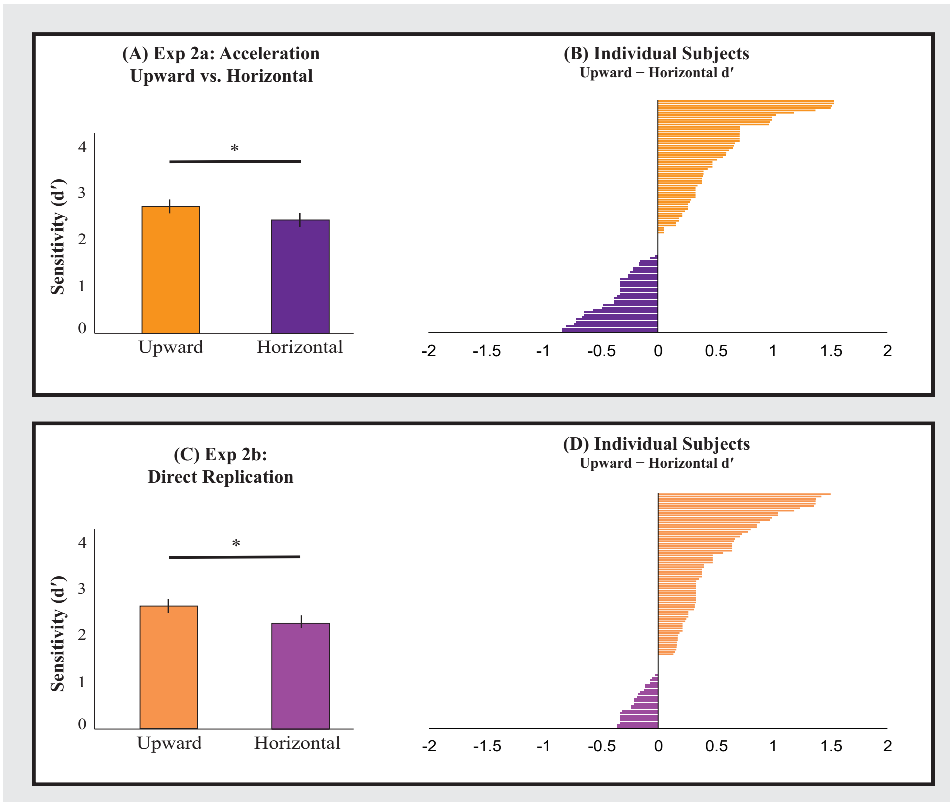
We next reran the experiment on a new sample of 100 subjects (53 female, 47 male; average age = 25.67 years, $SD = 4.26$). As depicted in Figure 3b, participants were again more sensitive to whether or not the object accelerated on Upward trials (d′ = 2.52) compared with Horizontal trials (d′ = 2.19), $t(99) = 7.07$, $p < .001$, $d_z = 0.71$—an effect that was again driven by higher hit rates in the Upward condition (HR = 0.78) than in the Horizontal condition (HR = 0.71), $t(99) = 5.66$, $p < .001$, $d_z = 0.57$. There was no difference in false alarm rate between the Upward (FA = 0.06) and Horizontal (FA = 0.07) conditions, $t(99) = 1.37$, $p = .175$, $d_z = 0.14$. A comparison of response criterion between Upward and Downward trials revealed that observers had a lower threshold to report acceleration when the object moved Upward ($\beta = 2.53$) than when it moved Horizontally ($\beta = 2.96$), $t(99) = 2.58$, $p = .011$, $d_z = 0.26$.

Discussion

Observers were better at detecting acceleration for Upward-moving objects than for Horizontally-moving objects.

Figure 3

(A) Sensitivity (d′ Values) for the Upward and Horizontal Conditions in Experiment 2a. (B) Sensitivity Difference Scores (Upward – Horizontal) for Individual Observers in Experiment 2a. (C) Sensitivity for the Upward and Horizontal Conditions in Experiment 2b. (D) Sensitivity Difference Scores (Upward – Horizontal) for Individual Observers in Experiment 2b



Note. See the online article for the color version of this figure.

These results indicate that the results of Experiment 1 (greater sensitivity to Upward vs. Downward acceleration) are driven, at least in part, by an *advantage* for detecting speed changes that are opposite to typical gravitational speed changes.

Experiment 3a: Acceleration Detection (Downward vs. Horizontal)

In Experiment 1, observers were more sensitive to an object's acceleration when it accelerated Upward (opposite to gravity) than when it accelerated Downward (consistent with gravity). In Experiment 2, observers were more sensitive when the object accelerated Upward than when it accelerated Horizontally (orthogonal to gravity). These results suggest a detection advantage for accelerations oriented opposite to gravity. Just out of curiosity, we next tested whether there is also a *dis*advantage to gravity-*consistent* acceleration, by comparing the detection of Downward acceleration to the detection of Horizontal acceleration.

Method

Experiment 3 was identical to Experiment 2, except as noted here.

Observers

One-hundred observers (47 female, 53 male; average age = 24.95 years, $SD = 4.03$) 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 to 100). The sample size was determined as follows: In a pilot experiment, a paired *t*-test revealed lower sensitivity to acceleration in Downward versus Horizontal trials, with an effect size of $d_z = 0.30$. A power analysis conducted using R's pwr library (Champely, 2020) indicated that we would need at least 87 subjects to detect this effect with 80% power at an α level of 0.05. We preregistered a sample size of 100 just to be safe.

Procedure

Observers again detected acceleration. The disc moved Downward on half of the trials and Horizontally on the other half. For half of the observers, Horizontal trials featured leftward movement and, for the other half, these trials featured rightward movement (but this did not have any effect on the results).

Results

We computed d′ for the Downward and Horizontal conditions. As depicted in Figure 4a, observers were less sensitive to whether or not the object accelerated on Downward trials (d′ = 2.30) compared with Horizontal trials (d′ = 2.55), $t(99) = 4.09$, $p < .001$, $d_z = 0.35$—an effect that was driven by lower hit rates in the Downward condition (HR = 0.72) than in the Horizontal condition (HR = 0.81), $t(99) = 5.24$, $p < .001$, $d_z = 0.48$. There was a significant difference in false alarm rate between the Downward (FA = 0.06) and Horizontal (FA = 0.08) conditions, $t(99) = 2.03$, $p = .046$, $d_z = 0.22$. A comparison of response criterion between Downward and Horizontal trials revealed that observers had a higher threshold to report acceleration when the object moved Downward ($\beta = 2.89$) than when it moved Horizontally ($\beta = 2.31$), $t(99) = 3.10$, $p = .003$, $d_z = 0.30$.

The pattern of sensitivity across the Downward and Horizontal conditions in the present experiment was qualitatively opposite to the pattern of sensitivity across the Upward and Horizontal conditions in Experiment 2. To confirm this, we computed the present observers' sensitivity differences between the Downward and Horizontal conditions, and for both Experiments 2a and 2b, computed observers' sensitivity differences between the Upward and Horizontal conditions. The difference scores in the present experiment were significantly different from those of both Experiment 2a (−0.25 vs. 0.21, $t(198) = 5.40$, $p < .001$, $d = 0.77$), and Experiment 2b (−0.25 vs. 0.33, $t(198) = 7.56$, $p < .001$, $d = 1.07$).

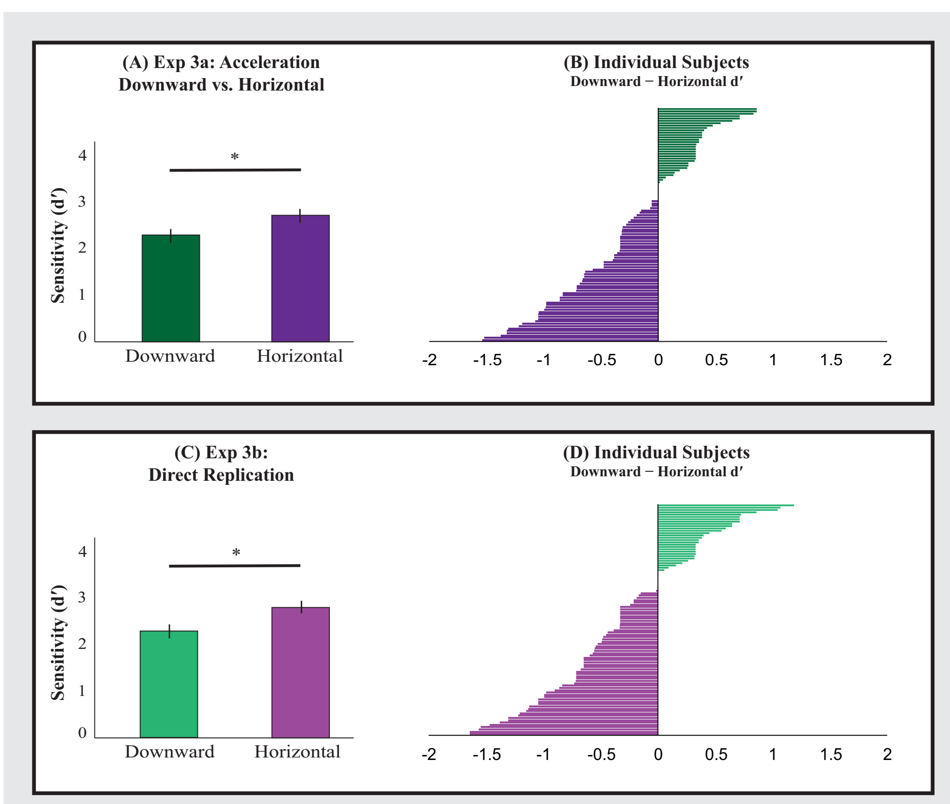
Experiment 3b: Direct Replication

We next directly replicated the experiment on a new sample of 100 subjects (58 female, 42 male; average age = 26.08 years, $SD = 4.88$).

As depicted in Figure 4b, observers were again less sensitive to whether or not the object accelerated on Downward trials (d′ = 2.29) compared with Horizontal trials (d′ = 2.61), $t(99) = 4.63$, $p < .001$, $d_z = 0.46$—an effect that was driven by lower hit rates in the Downward condition (HR = 0.72) than in the Horizontal condition (HR = 0.83), $t(99) = 5.92$, $p < .001$, $d_z = 0.59$. There was no difference in false alarm rate between the Downward (FA = 0.06) and Horizontal (FA = 0.07) conditions, $t(99) = 1.36$, $p = .177$, $d_z = 0.14$. A comparison of response criterion between Downward and Horizontal trials revealed that observers had a higher threshold to report acceleration when the object moved Downward ($\beta = 2.99$) than when it moved Horizontally ($\beta = 2.38$), $t(99) = 3.50$, $p < .001$, $d_z = 0.35$.

Figure 4

(A) Sensitivity (d′ Values) for the Downward and Horizontal Conditions in Experiment 3a. (B) Sensitivity Difference Scores (Downward – Horizontal) for Individual Observers in Experiment 3a. (C) Sensitivity for the Downward and Horizontal Conditions in Experiment 3b. (D) Sensitivity Difference Scores (Downward – Horizontal) for Individual Observers in Experiment 3b



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The pattern of sensitivity across the Downward and Horizontal conditions in the present experiment was qualitatively opposite to the pattern of sensitivity across the Upward and Horizontal conditions in Experiment 2. To confirm this, we computed the present observers' sensitivity differences between the Downward and Horizontal conditions, and for both Experiments 2a and 2b, computed observers' sensitivity differences between the Upward and Horizontal conditions. The difference scores in the present experiment were significantly different from those of both Experiment 2a (−0.31 vs. 0.21, $t(198) = 5.81$, $p < .001$, $d = 0.83$), and Experiment 2b (−0.31 vs. 0.33, $t(198) = 7.83$, $p < .001$, $d = 1.11$).

Discussion

Observers were worse at detecting acceleration for Downward-moving objects than for Horizontally moving objects. These results suggest that the results of Experiment 1 (greater sensitivity to Upward vs. Downward acceleration) reflect not only an advantage for Upward acceleration (as indicated by Experiment 2), but also a *dis*advantage for Downward acceleration.

Experiment 4a: Deceleration Detection (Upward vs. Downward)

The hypothesis that observers are more sensitive to speed changes opposite to gravity makes the reverse predictions for the detection of deceleration: If an upward-moving object decelerates, this deceleration is attributable to the force of gravity, and observers should be relatively insensitive to this. By contrast, if a downward-moving object decelerates, then this deceleration may be attributed to a "braking" force resisting gravity, in which case observers may be more sensitive to this. To test this prediction, we next ran a deceleration detection experiment, which was perfectly analogous to Experiment 1, except that now observers detected decelerations instead of accelerations.

Method

Experiment 4a was identical to Experiments 1a and 1b, except as noted here.

Observers

Fifty observers (25 female, 25 male; average age = 26.00 years, $SD = 4.53$) 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 to 100). The sample size was determined as follows: In a pilot experiment, a paired t-test revealed greater sensitivity to deceleration in Downward versus Upward trials, with an effect size of $d_z = 0.55$. A power analysis conducted using R's pwr library (Champely, 2020) indicated that we would need at least 42 subjects to detect this effect with 80% power at an α-level of 0.05. We preregistered a sample size of 50 just to be safe.

Stimuli

In both the Upward-moving and Downward-moving conditions, on half of the trials, the disc decelerated: it moved at a constant speed of 300 pix/s for 0.67 s, then decelerated at a rate of 144 pix/s^2 for 0.83 s, then moved at a constant speed of 180 pix/s for 2.22 s. On the other half of trials, the disc moved at a constant speed throughout: either at 180 pix/s (on half of the constant speed trials) or at 300 pix/s (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 5a, observers were more sensitive to whether or not an object decelerated on Downward trials (d′ = 2.93) compared with Upward trials (d′ = 2.44), $t(49) = 5.24$, $p < .001$, $d_z = 0.74$—an effect that was driven by higher hit rates in the Downward condition (HR = 0.90) than in the Upward condition (HR = 0.76), $t(49) = 6.17$, $p < .001$, $d_z = 0.87$. There was no difference in false alarm rate between Downward (FA = 0.08) and Upward (FA = 0.08) trials, $t(49) = 0.32$, $p = .749$, $d_z = 0.05$. A comparison of response criterion between Downward and Upward trials revealed that observers had a lower threshold to report deceleration when the object moved Downward ($\beta = 1.41$) than when it moved Upward ($\beta = 2.62$), $t(49) = 5.01$, $p < .001$, $d_z = 0.71$.

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, $t(98) = 6.55$, $p < .001$, $d = 0.62$) and Experiment 1b (−0.49 vs. 0.27, $t(98) = 6.09$, $p < .001$, $d = 0.63$).

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, $t(98) = 7.38$, $p < .001$, $d = 0.17$) and Experiment 1b (−0.14 vs. 0.11, $t(98) = 7.93$, $p < .001$, $d = 0.16$).

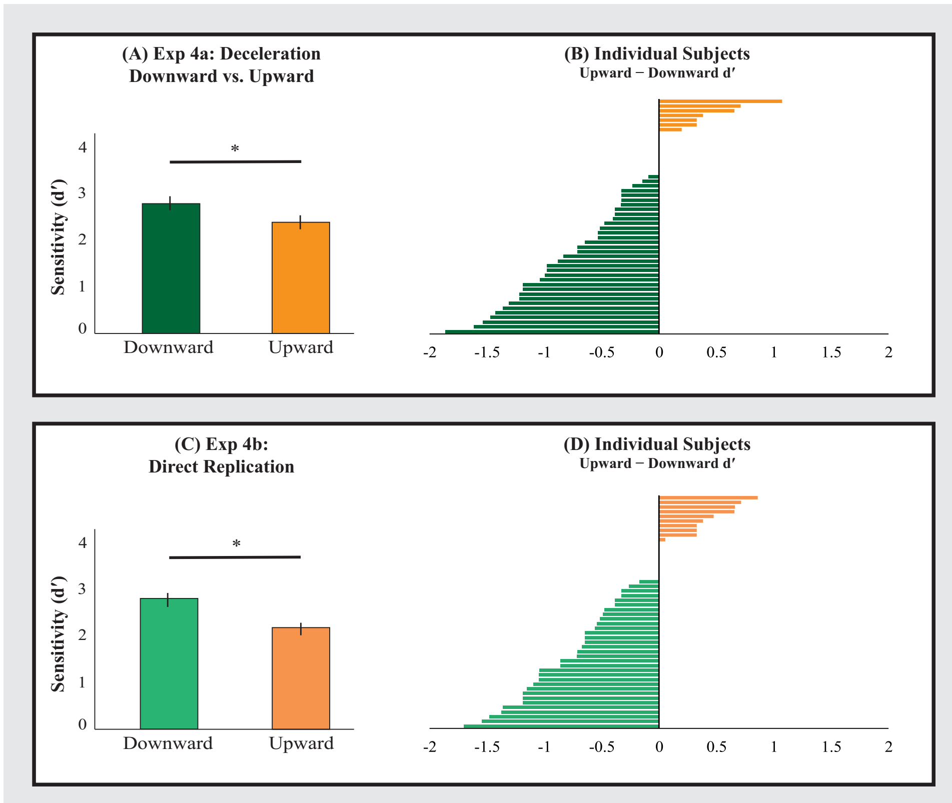
In contrast, observers' pattern of false alarm rates across the Upward and Downward conditions in this experiment was nonsystematic and qualitatively similar to the pattern of false alarm rates across the Upward and Downward conditions in the Acceleration Detection Experiments. To confirm this, we computed the Upward–Downward false alarm 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 false alarm rate difference scores in the present experiment did not differ from those of either Experiment 1a (0.00 vs. 0.02, $t(98) = 1.08$, $p = .284$, $d = 0.09$) or Experiment 1b (0.00 vs. 0.02, $t(98) = 1.29$, $p = .199$, $d = 0.07$).

Experiment 4b: Direct Replication

We next directly replicated the Deceleration Detection Experiment on a new sample of 50 subjects (15 female, 34 male, 1 nonbinary;

Figure 5

(A) Sensitivity (d′ Values) for the Downward and Upward Conditions in Experiment 4a (B) Sensitivity Difference Scores (Upward – Downward) for Individual Observers in Experiment 4a. (C) Sensitivity for the Downward and Upward Conditions in Experiment 4b. (B) Sensitivity Difference Scores (Upward – Downward) for Individual Observers in Experiment 4b



Note. See the online article for the color version of this figure.

average age = 25.26 years, $SD = 4.75$). 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 to 100).

The results of this replication are depicted in Figure 5b. Observers were again more sensitive to decelerations on Downward trials ($d' = 2.93$) compared with Upward trials ($d' = 2.50$), $t(49) = 4.74$, $p < .001$, $d_z = 0.67$—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), $t(49) = 5.86$, $p < .001$, $d_z = 0.82$. This time there was a significant difference in false alarm rate between Downward (FA = 0.07) and Upward (FA = 0.05) trials, $t(49) = 2.53$, $p = .015$, $d_z = 0.36$. A comparison of response criterion between Downward and Upward trials revealed that observers had a lower threshold to report deceleration when the object moved Downward ($\beta = 1.47$) than when it moved Upward ($\beta = 2.79$), $t(49) = 5.98$, $p < .001$, $d_z = 0.85$.

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 with 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, $t(98) = 6.17$, $p < .001$, $d = 0.61$) and Experiment 1b (−0.44 vs. 0.27, $t(98) = 5.72$, $p < .001$, $d = 0.62$).

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 with 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, $t(98) = 7.13$, $p < .001$, $d = 0.17$) and Experiment 1b (−0.13 vs. 0.11, $t(98) = 7.69$, $p < .001$, $d = 0.15$).

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, $t(98) = 2.27$, $p = .026$, $d = 0.07$) and Experiment 1b (−0.02 vs. 0.02, $t(98) = 2.96$, $p = .004$, $d = 0.06$).

Discussion

Observers were better at detecting decelerations 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 opposite to the force of gravity, compared with the same deceleration when it is consistent with gravitational acceleration.

Experiment 5a: Deceleration Detection (Downward vs. Horizontal Baseline)

In the previous experiment, observers were more sensitive to deceleration in downwardly-moving objects than in upwardly-moving objects. However, it remains possible that there is no advantage for detecting downward deceleration, and that observers are simply *less* sensitive to upward deceleration. To determine whether the previous effect was indeed partly driven by an advantage for detecting deceleration opposite to gravity, in Experiment 5, we compared deceleration detection in a Downward moving condition (which was identical to the Downward moving condition in the previous experiment) to deceleration detection in a new Horizontal baseline condition. Here stronger detection performance in the Downward relative to the Horizontal condition would support the hypothesis that we are more sensitive to deceleration opposite to gravity.

Method

Experiment 5a was identical to Experiments 4a and 4b, except as noted here.

Observers

One-hundred observers (37 female, 63 male; average age = 25.65 years, $SD = 4.14$) 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 to 100). The sample size was determined as follows: In a pilot experiment, a paired t-test revealed greater sensitivity to deceleration in Downward versus Horizontal trials, with an effect size of $d_z = 0.31$. A power analysis conducted using R's pwr library (Champely, 2020) indicated that we would need at least 82 subjects to detect this effect with 80% power at an α-level of 0.05. We preregistered a sample size of 100 just to be safe.

Procedure

Observers again detected Deceleration. The disc moved Downward on half of the trials and Horizontally on the other half. For half of the observers, Horizontal trials featured leftward movement and, for the other half, these trials featured rightward movement (but this did not have any effect on the results).

Results

We computed d′ for the Downward and Horizontal conditions. As depicted in Figure 6a, observers were more sensitive to whether or not an object decelerated on Downward trials (d′ = 2.96) compared with Horizontal trials (d′ = 2.78), $t(99) = 3.23$, $p = .002$, $d_z = 0.32$. There was no difference in hit rate between Downward (HR = 0.88) and Horizontal (HR = 0.88) trials, $t(99) = 0.55$, $p = .581$, $d_z = 0.06$. There was a significant difference in false alarm rate between Downward (FA = 0.05) and Horizontal (FA = 0.08) trials, $t(99) = 4.20$, $p < .001$, $d_z = 0.42$. A comparison of response criterion between Downward and Horizontal trials revealed that observers had a higher threshold to report deceleration when the object moved Downward ($\beta = 1.83$) than when it moved Horizontally ($\beta = 1.53$), $t(99) = 2.13$, $p = .035$, $d_z = 0.21$.

Experiment 5b: Direct Replication

We next directly replicated the experiment on a new sample of 100 subjects (51 female, 49 male; average age = 25.25 years, $SD = 3.99$). As depicted in Figure 6b, observers were again more sensitive to deceleration on Downward trials (d′ = 2.79) compared with Horizontal trials (d′ = 2.67), $t(99) = 2.09$, $p = .039$, $d_z = 0.21$. There was no difference in hit rate between Downward (HR = 0.87) and Horizontal (HR = 0.86) trials, $t(99) = 0.78$, $p = .436$, $d_z = 0.08$. There was no difference in false alarm rate between Downward (FA = 0.07) and Horizontal (FA = 0.09) trials, $t(99) = 1.89$, $p = .062$, $d_z = 0.19$. A comparison of response criterion between Downward and Horizontal trials revealed no difference between Downward ($\beta = 1.79$) and Horizontal ($\beta = 1.69$), $t(99) = 0.66$, $p = .509$, $d_z = 0.07$.

Discussion

Observers were better at detecting deceleration for Downward-moving objects than for Horizontally-moving objects. These results suggest that the results of Experiment 4 (greater sensitivity to Downward vs. Upward deceleration) were driven, at least in part, by an *advantage* for detecting speed changes that are opposite to typical gravitational speed changes.

Experiment 6a: Deceleration Detection (Upward vs. Horizontal Baseline)

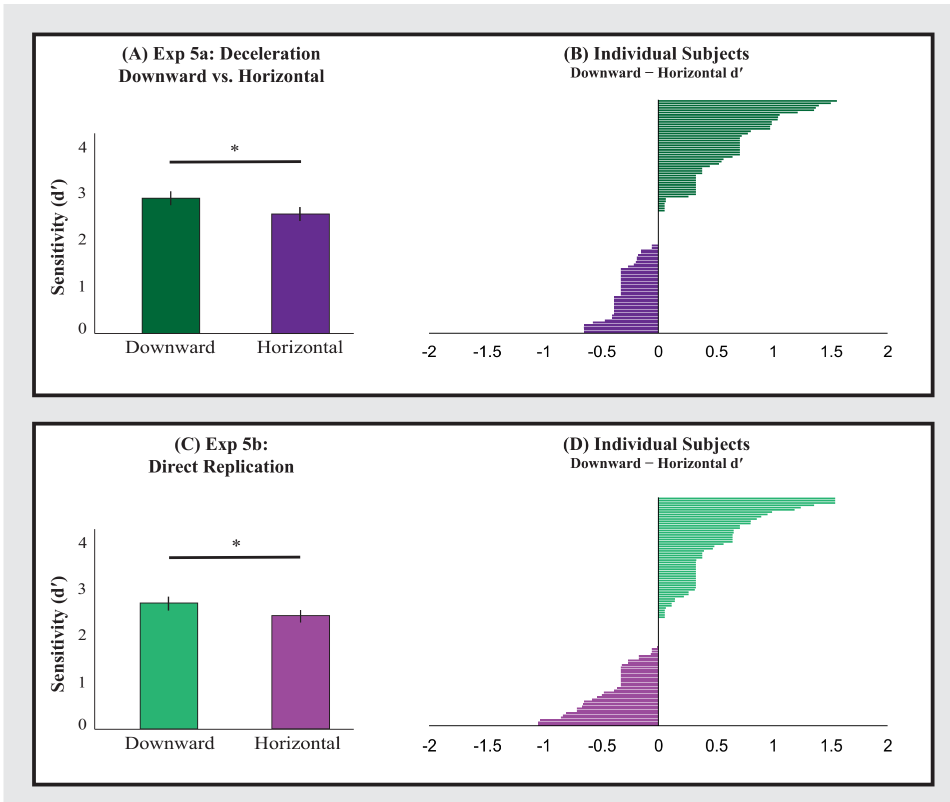
In Experiment 4, observers were more sensitive to deceleration when the object moved Downward (in which case the deceleration was opposite to gravity) than when it moved Upward (in which case the deceleration was consistent with gravity). In Experiment 5, observers were more sensitive to Downward deceleration compared with Horizontal deceleration (orthogonal with gravity). Together these results show an advantage for detecting deceleration opposite to gravity. Just out of curiosity, we next tested whether there is also a *dis*advantage to gravity-*consistent* deceleration, by comparing the detection of Upward deceleration to the detection of Horizontal deceleration.

Method

Experiment 6 was identical to Experiment 5, except as noted here.

Figure 6

(A) Sensitivity (d′ Values) for the Downward and Horizontal Conditions in Experiment 5a (B) Sensitivity Difference Scores (Downward – Horizontal) for Individual Observers in Experiment 5a. (C) Sensitivity for the Downward and Horizontal Conditions in Experiment 5b. (D) Sensitivity Difference Scores (Downward – Horizontal) for Individual Observers in Experiment 5b



Note. See the online article for the color version of this figure.

Observers

One-hundred observers (50 female, 50 male; average age = 25.24 years, $SD = 3.85$) 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 to 100). The sample size was determined as follows: In a pilot experiment, a paired *t*-test revealed lower sensitivity to deceleration in Upward versus Horizontal trials, with an effect size of $d_z = 0.55$. A power analysis conducted using R's pwr library (Champely, 2020) indicated that we would need at least 78 subjects to detect this effect with 80% power at an α-level of 0.05. We preregistered a sample size of 100 just to be safe.

Procedure

Observers again detected deceleration. The disc moved Upward on half of the trials and Horizontally on the other half. For half of the observers, Horizontal trials featured leftward movement and, for the other half, these trials featured rightward movement (but this did not have any effect on the results).

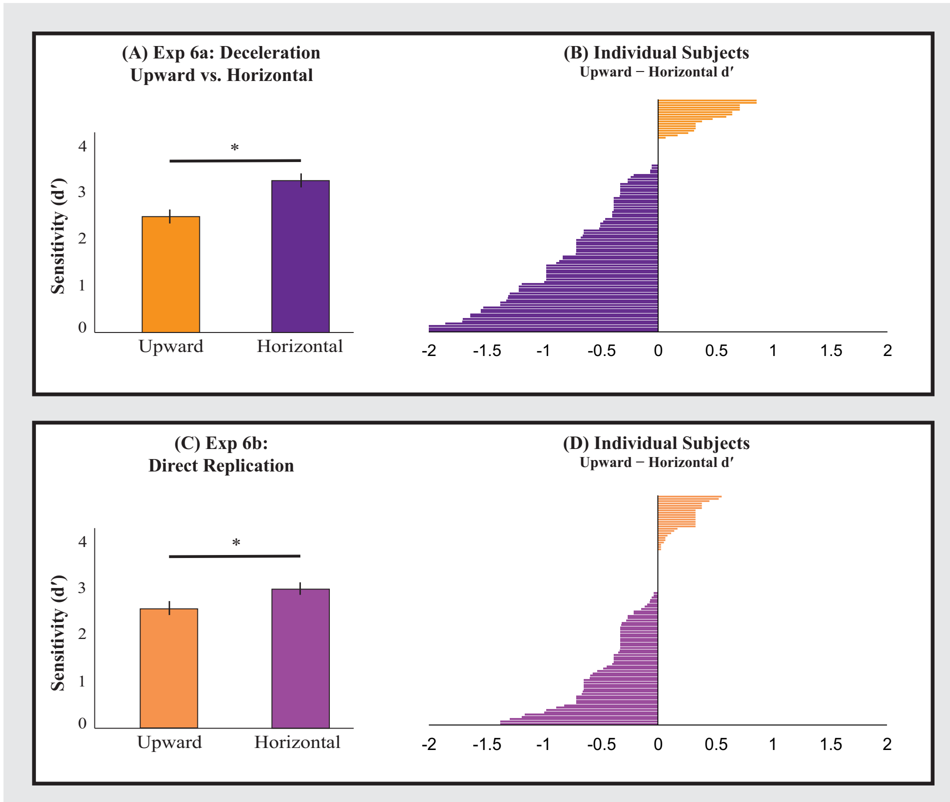
Results

We computed d′ for the Upward and Horizontal conditions. As depicted in Figure 7a, observers were less sensitive to whether or not an object decelerated on Upward trials (d′ = 2.53) compared with Horizontal trials (d′ = 3.05), $t(99) = 7.26$, $p < .001$, $d_z = 0.73$—an effect that was driven by lower hit rates in the Upward condition (HR = 0.76) than in the Horizontal condition (HR = 0.92), $t(99) = 9.74$, $p < .001$, $d_z = 0.97$. There was a significant difference in false alarm rate between Upward (FA = 0.03) and Horizontal (FA = 0.05) trials, $t(99) = 2.70$, $p = .008$, $d_z = 0.27$. A comparison of response criterion between Upward and Horizontal trials revealed that observers had a higher threshold to report deceleration when the object moved Upward ($\beta = 3.02$) than when it moved Horizontally ($\beta = 1.60$), $t(99) = 8.40$, $p < .001$, $d_z = 0.84$.

The pattern of sensitivity across the Upward and Horizontal conditions in the present experiment was qualitatively opposite to the pattern of sensitivity across the Downward and Horizontal conditions in Experiment 5. To confirm this, we computed the present observers' sensitivity differences between the Upward and Horizontal conditions, and for both Experiments 5a and 5b, computed observers' sensitivity differences between the Downward and Horizontal conditions. The

Figure 7

(A) Sensitivity (d′ Values) for the Upward and Horizontal Conditions in Experiment 6a (B) Sensitivity Difference Scores (Upward – Horizontal) for Individual Observers in Experiment 6a. (C) Sensitivity for the Upward and Horizontal Conditions in Experiment 6b. (D) Sensitivity Difference Scores (Upward – Horizontal) for Individual Observers in Experiment 6b



Note. See the online article for the color version of this figure.

difference scores in the present experiment were significantly different from those of both Experiment 5a (−0.52 vs. 0.18, $t(98) = 7.71$, $p < .001$, $d = 1.10$) and Experiment 5b (−0.52 vs. 0.12, $t(98) = 6.91$, $p < .001$, $d = 0.98$).

Experiment 6b: Direct Replication

We next directly replicated the experiment on a new sample of 100 subjects (50 female, 50 male, average age = 25.81 years, $SD = 4.69$). 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 to 100).

As depicted in Figure 7b, observers were again less sensitive to decelerations on Upward trials ($d' = 2.66$) compared with Horizontal trials ($d' = 2.90$), $t(99) = 5.18$, $p < .001$, $d_z = 0.52$—an effect that was driven by lower hit rates in the Upward condition (HR = 0.79) than in the Horizontal condition (HR = 0.89), $t(99) = 8.36$, $p < .001$, $d_z = 0.84$. There was a significant difference in false alarm rate between Upward (FA = 0.04) and Horizontal (FA = 0.06) trials, $t(99) = 4.25$, $p < .001$, $d_z = 0.43$. A comparison of response criterion between Upward and Horizontal trials revealed that observers had a higher threshold to report deceleration when the object moved Upward ($\beta = 2.62$) than when it moved Horizontally ($\beta = 1.56$), $t(99) = 7.03$, $p < .001$, $d_z = 0.70$.

The pattern of sensitivity across the Upward and Horizontal conditions in the present experiment was qualitatively opposite to the pattern of sensitivity across the Downward and Horizontal conditions in Experiment 5. To confirm this, we computed the present observers' sensitivity differences between the Downward and Horizontal conditions, and for both Experiments 5a and 5b, computed observers' sensitivity differences between the Upward and Horizontal conditions. The difference scores in the present experiment were significantly different from those of both Experiment 5a (−0.24 vs. 0.18, $t(198) = 5.78$, $p < .001$, $d = 0.82$) and Experiment 5b (−0.24 vs. 0.12, $t(198) = 4.81$, $p < .001$, $d = 0.68$).

Discussion

Observers were worse at detecting deceleration for Upward-moving objects than for Horizontally-moving objects.

These results suggest that the results of Experiment 4 (greater sensitivity to Downward vs. Upward deceleration) reflect not only an advantage for Downward deceleration (as demonstrated by Experiment 5) but also a *dis*advantage for Upward deceleration.

General Discussion

In six experiments, consistent with the hypothesis that we monitor the world for self-propelled movements, observers were more sensitive to objects' speed changes when those speed changes were opposite to gravity. In Experiment 1, observers were more sensitive to upward acceleration than to downward acceleration. In Experiment 2, upward acceleration was detected more readily than horizontal acceleration, suggesting the initial difference was driven in part by an advantage for speed changes opposite to gravity. In Experiment 3, observers were less sensitive to downward acceleration compared with horizontal acceleration, suggesting that the initial difference was also driven partly by a *dis*advantage for speed changes consistent with gravity. These patterns were mirrored in three experiments testing deceleration sensitivity: In Experiment 4, deceleration was detected more readily for downwardly-moving objects than for upwardly-moving objects. In Experiment 5, observers were more sensitive to downward deceleration compared with horizontal deceleration, suggesting that the difference in Experiment 4 was driven in part by an advantage for deceleration opposite to gravity. In Experiment 6, observers were less sensitive to upward deceleration compared with horizontal deceleration, suggesting that the difference in Experiment 4 was also driven partly by a *dis*advantage for deceleration consistent with gravity. Thus, observers were more sensitive to speed changes opposite to gravity and less sensitive to speed changes consistent with gravity.

We are confident in the results that form the basis for this conclusion, as they were highly replicable, with two preregistered, high-powered replications of every experiment. Moreover, these effects were observed under well-controlled conditions, with the same exact speed changes detected differentially well depending only on how they were oriented. (Although the present work prioritized experimental control, in future work, it will be important to confirm that the same effects also obtain with more naturalistic stimuli.) This orientation-dependence in the detection of speed changes appears to reflect a fundamental limit in visual processing, as it emerged in detection sensitivity (d')—even when observers were trying their best to detect the speed changes in all conditions.

Prioritization of Animacy in Visual Cognition

Our prediction that subjects would be more sensitive to speed changes opposite to gravity was based on recent 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, 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 causes 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 with 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 opposite to natural gravitational acceleration, are consonant with the widespread 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).

"Gravity Priors" in Visuomotor Behavior and Memory

As reviewed in the introduction, visually guided interception evinces a strong assumption of gravity-consistent acceleration (e.g., McIntyre et al., 2001; Zago et al., 2004). And similarly, memory for recently-seen objects' positions also shows a gravitational bias: When observers briefly view a single moving object, and must report its last visible position, they tend to 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). Such memory displacements are larger for downwardly-moving objects than for upwardly-moving objects, suggesting that memory encodes an implicit model of the force of gravity (e.g., Hubbard & Bharucha, 1988; for a review see Hubbard, 2020). In further support of this, downward displacements in visual memory—termed "representational gravity"—have also been observed for horizontally moving objects (Hubbard, 1990; Hubbard & Bharucha, 1988), and for 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). Like the gravity bias in visually guided interception behavior, this memory bias may help to ensure accuracy when remembering the locations of unsupported objects, by factoring in how they are likely to move, given gravity (for a review, see Jörges & López-Moliner, 2017).

When reaching out to grab an object, or remembering precisely where it was, visual processing ought to be biased toward how it is most likely to move. However, the present work, on visual detection of objects' speed changes, suggests that implicit knowledge of gravity may not be used in a uniform way across different visual tasks. When detecting whether or not an object changed speed, observers were more sensitive to speed changes *opposite* to gravity and did not show a response bias toward reporting gravity-consistent speed changes. When it comes to noticing whether or not an object has changed the speed in the first place, detection performance is tuned not to what is most likely, but rather to what *matters*—namely, behaviors which appear self-propelled and animate. These results are consistent with the broad view that perception is tuned to what is important to us, and not necessarily tuned to "truth" (Hoffman et al., 2015; c.f. Berke et al., 2022).

Implicit Versus Explicit Knowledge of Gravity

In addition to demonstrations of implicit knowledge of physics in perception and memory, there have also been several studies exploring how subjects *explicitly reason* about physical structures and events. When asked whether a 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 point-light animations, 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 generally competent at explicit physical reasoning during online perception, they do much 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 visually guided motor behavior 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). Are the present results more akin to the former, or to the latter? We think it is clear that our results reflect the implicit tuning of visual detection to speed changes opposite to gravity, rather than observers' explicit reasoning. First, observers performed a straightforward visual task in which they simply had to report whether or not a moving object changed speed. There was no indication to subjects that outside knowledge or explicit reasoning about physics would be useful in performing this task. Second, responses were fast (365 ms on average across experiments), leaving little time for deliberate reasoning. Third, during debriefing, when observers were asked to report what strategies they used to detect the speed changes, 0/1,000 observers referred to gravity or physics (instead, they mentioned a variety of visual strategies, e.g., "I squinted my eyes to increase my focus, so I could zoom in on the ball.", "I didn't pay attention to only the dot, I tried to look at the screen as a whole and from a distance to be able to see the bigger picture.", "I stared at the center of the screen and not directly to the object.", "I merely tried to follow the black ball with my eyes and try to notice if it sped up or not."). In these experiments, observers' greater sensitivity to speed changes opposite to gravity arose via implicit constraints on motion processing, rather than via their explicit deliberation about when speed changes should occur.

Can Eye Movements Explain These Results?

Across all six experiments, in their debriefing responses, a small minority (1.3%) of subjects mentioned using a deliberate strategy of fixating on the center of the screen and not tracking the object with their eyes. Conversely, another small minority (1.5%) mentioned deliberately tracking the object with their eyes. Without eye-tracking data, we cannot be sure how most subjects fixated on our displays. However, it seems reasonable to think that most tracked the object with their eyes, even if they did not report this strategy later on. Smooth pursuit eye movements have greater fidelity when tracking horizontally, relative to vertically moving targets (Leung & Kettner, 1997; Rottach et al., 1996). Moreover, smoothly pursuing a target has been found to improve heading discrimination (Miyamoto et al., 2021; Spering et al., 2011) and, depending on the study, can make speed judgments either more accurate (de la Malla et al., 2022) or less accurate (Freeman et al., 2010). Could our results be explained by some combination of these effects?

If our subjects were better at tracking horizontally moving targets than vertically moving targets, and if better smooth pursuit in our study was associated with greater sensitivity to speed differences (as was found by de la Malla et al., 2022), then this could have contributed to subjects' greater sensitivity to the accelerations of horizontally versus downwardly-moving objects in Experiment 3. But this hypothesis (unlike the more parsimonious "better sensitivity to speed changes opposite to gravity" hypothesis) leaves unexplained why subjects were later *less* sensitive to the decelerations of horizontally versus downwardly-moving objects in Experiment 5. Similarly, better tracking of horizontally moving targets, combined with greater sensitivity to the speed changes of smoothly pursued objects, could have contributed to subjects' greater sensitivity to the decelerations of horizontally versus upwardly-moving objects in Experiment 6, but cannot explain why subjects were worse at detecting the accelerations of horizontally versus upwardly-moving objects in Experiment 2. Finally, some have reported better tracking of downwardly-moving targets than upwardly-moving ones (Ke et al., 2013), although this effect appears to be less reliable than the pursuit advantage for horizontally moving targets relative to vertically moving ones (Takeichi et al., 2003). Such an effect, coupled with better sensitivity to speed changes during smooth pursuit (which again, is also debated; Freeman et al., 2010), could have contributed to subjects' greater sensitivity to the decelerations of downwardly versus upwardly-moving objects in Experiment 4, but cannot explain why subjects were better at detecting the accelerations of upwardly versus downwardly-moving objects in Experiment 1.

Future work should replicate our results in the lab with an eye tracker. However, it is already clear that the present results cannot be attributed to established effects of smooth pursuit eye movements on the perception of moving objects. First, there is disagreement about whether smooth pursuit makes us more sensitive, or less sensitive, to objects' speeds. Second, regardless, smooth pursuit anisotropies cannot explain why the pattern of performance across conditions in the acceleration detection experiments (Experiments 1–3) flipped in the deceleration detection experiments (Experiments 4–6). In contrast, the hypothesis that we are better at detecting speed changes opposite to gravity (and worse at detecting speed changes consistent with gravity) explains the pattern of results across all six experiments.

Conclusion: Linking "Animate Monitoring" to Motion Perception

It has been proposed that visuomotor behavior and memory rely on an implicit, interiorized representation of earth's gravity, and more specifically, that a strong "gravity prior" biases our perception and memory of objects' movements in the direction of gravitational acceleration (Jörges & López-Moliner, 2017). The present results support the first half of this claim—that knowledge of physical forces (and causation more generally) is implicitly embedded in the operation of visual processes. However, our results provide an important counterpoint to the notion of a widespread gravity prior. In a visual detection task in which observers had to report whether or not a speed change occurred, they were much more sensitive when speed changes were opposite to gravity, and they tended to be biased to report gravity-*in*consistent speed changes. Thus, when it comes to noticing a speed change in the first place, perception may be tuned to those speed changes which matter most, due to appearing alive and self-propelled.

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