THE PERCEPTION OF FALLING OBJECTS

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Abstract

Aristotle believed that objects fell at a constant velocity, which raised the possibility that people's visual perception of falling motion might be biased away from acceleration towards constant velocity. I tested this idea by requiring participants to judge whether a ball moving in a simulated naturalistic setting appeared to accelerate or decelerate, as a function of its motion direction and the amount of acceleration/deceleration. I found that the point of subjective constant velocity (PSCV) differed between up and down but not between left and right motion directions, which indicated that more acceleration was needed for a downward-falling object to appear at constant velocity than for an upward "falling" object. I found no significant differences in sensitivity to acceleration for the different motion directions. My results support the idea that Aristotle's belief may in part be due to a bias that reduces the perceived magnitude of acceleration for falling objects.

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1.0. Introduction

Human perception has long been a subject of fascination and inquiry across various disciplines, from philosophy to psychology and beyond. One of the intriguing historical debates about this topic revolves around Aristotle's conception of falling objects and their perceived motion. Aristotle, a notable philosopher and polymath, believed that objects fall at constant speed (Hardcastle, 1914; Nature editorial, 1946). This idea had prevailed for centuries until Galileo Galilei's groundbreaking insights challenged this assumption. Galileo demonstrated that gravity, rather than causing objects to fall at constant velocity, actually induces acceleration in falling objects (Galilei, 1638). Aristotle's mistaken claim raises the possibility that people's visual perception of falling motion might be biased towards perceiving it as a constant speed rather than recognizing the true acceleration involved. This thesis investigates this possibility.

Understanding how individuals perceive the movement of objects in their environment has been a central focus of research in neuroscience and psychology. For instance, research by Cavanagh (1992) has highlighted the role of attention in motion perception, emphasizing its influence on the perceptual experience of object movement. Another study by Goodale and Milner (1992) have found evidence for Click here to enter text.separate visual pathways for perception and action, contributing to our understanding of how the brain processes visual information related to motion and object interaction. One aspect of this inquiry concerns the perception of acceleration and deceleration, especially in the context of downward motion (Calderone & Kaiser, 1989; Nguyen and van Buren, 2023). Contemporary research in visual perception has explored various aspects of motion perception, including directionality and velocity. However, few studies have directly addressed the possibility of a constant velocity bias in perceiving falling motion. One notable study by Burr and Ross (1982) investigated the perception of velocity in moving stimuli and found evidence for systematic biases in perception, particularly for the perception of acceleration. They found that observers consistently misjudged the velocity of accelerating stimuli, perceiving them to be moving at a different speed than their actual velocity. The study also revealed that the effect of motion on contrast sensitivity is directionally specific. In other words, the perception of contrast differs depending on the direction of motion (e.g., horizontal vs. vertical motion). Such a systematic bias in perceiving velocity has implications for the perception of falling objects. When objects fall, they of course accelerate due to gravity. However, if observers were to have a systematic bias when perceiving acceleration, they may inaccurately perceive the speed of falling objects. For example, they may perceive a falling object to be moving at a constant velocity when, in reality, it is accelerating due to gravity. Such a misperception of falling motion suggests that individuals may not accurately perceive the true acceleration of falling objects, leading to potential errors or biases in their perception of falling motion. Investigating the perception of falling motion could shed light on how our visual system interprets gravitational effects and shapes our understanding of the physical world.

Previous studies have measured how sensitive we are to acceleration (Calderone & Kaiser, 1989; Lee et al., 2019; Mueller & Timney, 2016; Nakayama & Motoyoshi, 2017; Nguyen & van Buren, 2023; Schmerler, 1976; Watamaniuk & Heinen, 2003; Werkhoven et al., 1992) and found that the human visual system is only a little or even not sensitive at all to the acceleration of a moving stimulus. The research most relevant to this thesis is by Nguyen and van Buren (2023), who measured sensitivity to acceleration as a function of motion direction. Their results showed that observers were more sensitive to acceleration when objects moved upwards and were less sensitive when objects moved downwards. Moreover, their findings also indicated that observers were least accurate at detecting deceleration when objects moved upwards and most accurate when objects moved downwards. The conclusions of this study support the foundation of my hypothesis because they suggest a directional bias in the perception of acceleration.

There are not many studies that have considered whether participants might be biased in their discrimination of whether something is accelerating or decelerating depending on the direction of motion (Calderone & Kaiser, 1989; Nguyen and van Buren, 2023), which is what my thesis investigates. Here I examine the possibility that there might be a perceptual bias in the perception of falling objects. As gravity is the most consistent force in our environment, it is more common for us to see objects accelerating downward compared to other directions. Consequently, when an object undergoes downward acceleration, it may feel more natural. By manipulating motion direction and acceleration, I assessed individuals' judgments of the motion of falling objects: in particular, whether they thought they were accelerating or not.

1.1. Internal Model of Gravity

Gravity, as described by Newton's law of universal gravitation, is a fundamental force that governs the attraction between objects with mass. Gravity shapes various aspects of human perception and our interaction with the environment. As noted by Volkmann and Baluška (2006), gravity stands as a defining force in the evolution of mechanical forms, which is the foundation for the development and functioning of biological organisms and mechanical structures alike. Furthermore, research spanning several decades has emphasized the pivotal role of gravity in our perception of our environment (Dichgans et al., 1972; Merfeld et al., 1999; Rosenberg and Angelaki, 2014). These studies highlight how gravity acts as a reference, guiding our spatial awareness and influencing how we perceive motion and orientation in relation to the Earth's gravitational field. Gravity also sets fundamental constraints on human interactions with the world, shaping movement patterns and motor control (Crevecoeur et al., 2014). Gravity significantly affects how we move, stand, and use our hands by influencing our body mechanics and nerves, which determines how well we can perform tasks.

Internal model of gravity refers to the inherent tendency for individuals to perceive motion influenced by gravity differently from other motions. Such a potential bias stems from several factors related to humans' understanding and experience of gravitational forces. Humans possess an innate understanding of gravity due to our constant exposure to its effects (Laurens & Angelaki, 2011). From infancy, individuals have learned to adapt, navigate and interact with their environment under the influence of gravity, leading to an established familiarity with its effects on motion (Rosenberg & Angelaki, 2018). Additionally, studies have demonstrated the impact of altered gravity conditions on perception, highlighting the role of gravity in shaping spatial orientation and motion perception (Kornilova, 2021). Considering the vertical alignment of gravitational forces is a key aspect contributing to any potential gravity perception bias, it is possible that motion aligned with the direction of gravity, i.e. downward or upward motion, may be perceived as more consistent or predictable.

Moreover, it is likely that individuals would develop expectations regarding falling objects due to their experiences with gravity in their daily life. However, there could be an erroneous assumption that objects will fall at a constant rate, shaped by continuous exposure to gravitational effects and the difficulty of distinguishing an acceleration of 9.8m/s/s from movement at a constant velocity, as continuous exposure to a visual pattern biases our subsequent perception of that pattern (Webster, 2015). More specifically, downward motion might need more acceleration compared to motion in other directions in order to be detected due to people being less sensitive to gravity-related motion.

1.2. Hypothesis

Consider an object with a motion profile that varies continuously from deceleration (which is just negative acceleration) through constant velocity to acceleration. Any perceptual bias will tend to shift the point at which that object is perceived to be moving at constant velocity. I refer to that point as the "point of subjective constant velocity," or PSCV. If an object appears to accelerate less when moving downwards than when it is moving in other directions, then this would reveal itself as a shift of the downwards PSCV towards the acceleration end of the continuum. Similarly, for upwards-moving objects that in our everyday experience tend to decelerate, the bias would shift the PSCV towards the deceleration end of the continuum. I therefore hypothesize such a bias. Since there is no inherent gravitational bias or asymmetry in the forces affecting objects moving horizontally, leftwards and rightwards moving objects would be expected to accelerate or decelerate equally. Therefore, I hypothesize no difference in their PSCVs.

There is a potential confusion between sensitivity and bias here. The distinction between sensitivity and bias in the context of the present study is illustrated in Figure 1. The figure shows hypothetical psychometric functions of the percentage of "it's accelerating" responses as a function of acceleration when asked if a moving object was accelerating or decelerating. The blue and orange curves are hypothetical responses to two directions of motion with the same PSCV but different slopes, that is, different sensitivities. The blue and red curves are hypothetical responses to two directions of motion with the same sensitivities but different biases, that is, different PSCVs. Such a bias shift would indicate that for the red motion direction the object appears to accelerate less for a given acceleration compared to the blue motion direction.

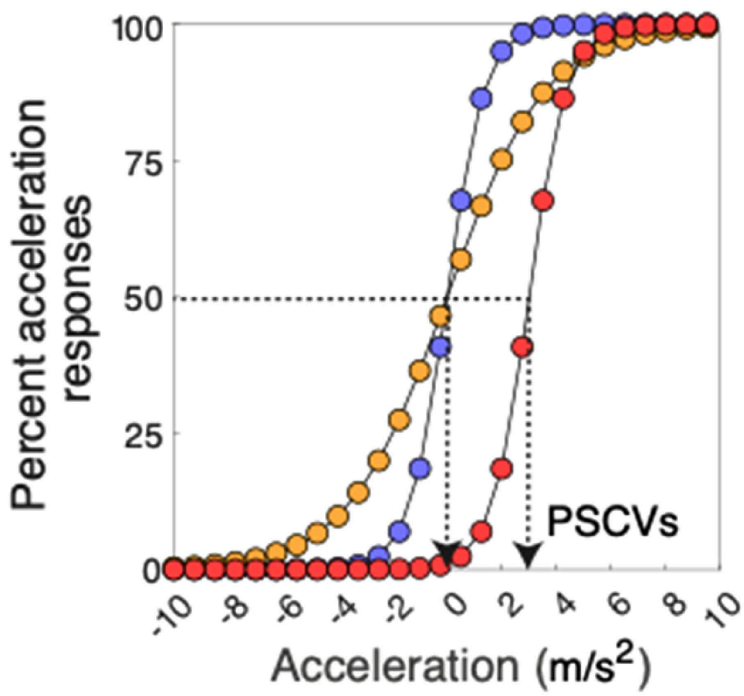

Figure 1: Hypothetical psychometric functions describing the percentage of "acceleration" responses as a function of acceleration for three motion directions given by the blue, orange and red curves. Negative values on the abscissa are decelerations. PSCV = point of subjective constant velocity. The difference between the blue and yellow curves is in terms of their slopes indicating a change in sensitivity. The difference between the blue and red curves is in terms of their positions along the abscissa, indicating a change in bias.

In my study, a basketball moved randomly from left to right, right to left, top to bottom, or bottom to top of the computer screen, with a simulated travel distance of 4 meters and a fixed transit time to eliminate transit time as a cue for acceleration or deceleration perception. Participants indicated whether they perceived the basketball as accelerating or decelerating. This was achieved by manipulating the initial velocity of the ball when it first appeared. I chose to use a basketball to provide a familiar object of a familiar size for participants, aiding in their perception of the relative size and height of the room. With this design, it is worth noting which aspect of the motion observers might use to make their decision as to whether the ball was accelerating or decelerating. For a moving object, duration, distance, acceleration, and initial velocity all co-vary. There were four different conditions, each with different transit times (1 s, 1.25 s, 1.5 s and 1.75 s). Within each condition, I kept the distance and transit time fixed. In order to do this, initial velocity had to co-vary with the acceleration. The question therefore arose as to which cue participants might rely upon to make their judgments as to whether the ball was accelerating or decelerating. Given that we have 4 different transit times in our study, the initial velocity and acceleration are not perfectly correlated. Therefore, to confirm that participants were depending more on the acceleration of the ball than its initial velocity, I used a generalized linear mixed model. This analysis allowed for the examination of how much multiple factors, particularly the acceleration of the ball and its initial velocity, contributed to participants' judgments of whether the ball was accelerating or decelerating. My hypothesis was that objects moving downwards will be perceived to accelerate less and decelerate more than objects moving in other directions with the same acceleration/deceleration, and thus PSCV for downwards-moving objects will be shifted towards the acceleration end of the spectrum compared to the PCSV for objects moving in other directions.

2.0. Methods

2.1. Participants

The study was conducted online using Pavlovia, after getting approved by the York University ethics board (Certificate # e2021-333). There were 88 participants in Group 1 and 74 participants in Group 2. All participants were students enrolled at York University, and they were given course credits in exchange. All participants had normal or corrected-to-normal vision and were required to provide written informed consent.

2.2. Stimuli

Participants judged whether a basketball moving in one of the cardinal directions (up, down, left, right) was accelerating or decelerating as it travelled across a room. The virtual environment was shown on their computer screens at home, in full screen mode. The study was designed so that it could not be run on any other devices, such as tablets or phones. The frame rate was set at 60 Hz. The participants were asked to view the simulated room while maintaining fixation on a cross at the center of the screen. On each trial, a basketball was animated, frame by frame, to move across the screen either from left to right, right to left, top to bottom, or bottom to top. The travel distance was simulated at 4 meters, scaled using the sizes of several reference objects such as a door, people, and the basketball itself, as shown in Figure 2. The ball appeared through one of the holes in the room at an initial velocity chosen such that whether it accelerated or decelerated, the time it would take to cross the room would be fixed at one of four transit times to eliminate transit time as a cue for whether the ball was accelerating or decelerating.

Figure 2: The virtual environment as observed by participants. The fixation cross at the center of the screen and the people and door provided the scale for the 4 m square room.

The experiment used two groups of participants. For Group 1 (n = 88), transit times of 1 s and 1.5 s were used. For Group 2 (n = 74), transit times of 1.25 s and 1.75 s were used. For each transit time, there were 11 equally spaced acceleration values between ± 8 $m \cdot s^{-2}$ for a transit time of 1 s, ± 5.1 $m \cdot s^{-2}$ for a transit time of 1.25 s, ± 3.56 $m \cdot s^{-2}$ for a transit time of 1.5 s, and ± 2.61 $m \cdot s^{-2}$ for a transit time of 1.75 s. The number of times each acceleration/deceleration value presented was determined according to an approximate Gaussian distribution, with high acceleration/deceleration values presented less often than low acceleration/deceleration values (see the final column of Tables 1a and 1b). This feature maximized the number of values around the expected PSCV where the acceleration is close to 0 $m \cdot s^{-2}$ (i.e., constant velocity) and kept the data collection time to a minimum. This enabled me to conduct a detailed analysis of the values of interest to determine if there was a perceptual bias in PSCV between different directions.

Table 1a: Conditions for Group 1

Initial Velocity (m/s)	Acceleration (m/s^2)	Duration (s)	Repetitions
0	8	1	2
0.8	6.4	1	3
1.6	4.8	1	5
2.4	3.2	1	7
3.2	1.6	1	9
4	0	1	10
4.8	-1.6	1	9
5.6	-3.2	1	7
6.4	-4.8	1	5
7.2	-6.4	1	3
8	-8	1	2
0	3.56	1.5	2
0.53	2.84	1.5	3
1.07	2.13	1.5	5
1.6	1.42	1.5	7
2.13	0.71	1.5	9
2.67	0	1.5	10
3.2	-0.71	1.5	9
3.73	-1.42	1.5	7
4.27	-2.13	1.5	5
4.8	-2.84	1.5	3
5.33	-3.56	1.5	2

Table 1b: Conditions for Group 2

Initial Velocity (m/s)	Acceleration (m/s^2)	Duration (s)	Repetitions
6.4	-5.12	1.25	2
5.76	-4.1	1.25	3
5.12	-3.07	1.25	5
4.48	-2.05	1.25	7
3.84	-1.02	1.25	9
3.2	0	1.25	10
2.56	1.02	1.25	9
1.92	2.05	1.25	7
1.28	3.07	1.25	5
0.64	4.1	1.25	3
0	5.12	1.25	2
4.57	-2.61	1.75	2
4.11	-2.09	1.75	3
3.66	-1.57	1.75	5
3.2	-1.04	1.75	7
2.74	-0.52	1.75	9
2.29	0	1.75	10
1.83	0.52	1.75	9
1.37	1.04	1.75	7
0.91	1.57	1.75	5
0.46	2.09	1.75	3
0	2.61	1.75	2

2.3. Procedure

At the start of the experiment the participant was given instructions and did 10 practice trials with relatively high levels of acceleration and deceleration to make the decisions easy and in order to become familiar with the task. Feedback (a green tick for correct and a red cross for incorrect) was provided for the practice trials but no feedback was provided during the main experiment. On each trial, once the ball crossed the room, the participant would respond "accelerating" or "decelerating" by pressing the left or right arrow keys. For half the participants left meant accelerating and for half of them right meant accelerating. Written instructions about which keys they should use were given at the start of the experiment. There were 124 trials for each direction and 496 trials in total (for both groups) and the experiment took around 20 minutes to complete.

2.4. Analysis

For each participant and condition, the percentage of times "accelerating" was chosen (*pA*) was plotted against the deceleration or acceleration value *x*, and the resulting psychometric function was fitted with a Logistic function with weightings applied to each point according to the number of times each value of acceleration had been presented. This was important because of the uneven distribution of repetitions for each acceleration value (Table 1). For this purpose, I used the function PAL_PFML_Fit in the Palamedes toolbox (Prins & Kingdom, 2016).

$$pA = 100/[1 + exp^{-b(x-a)}] \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where *pA* is the percentage of acceleration responses, *x* is the deceleration or acceleration value, *a* is the estimate of the PSCV and *b* the slope of the function. Outliers were removed using the criteria that the absolute value of the PSCV had to be within ± 20 $m \cdot s^{-2}$ and the slope had to be less than 10 $m \cdot s^{-2}$. Participants' data which did not satisfy these criteria for both motion directions and for both transit times was discarded. For the Down vs Up analysis, 59 participants from Group 1 and 58 participants from Group 2 were included. For the Left vs Right analysis, 57 participants from Group 1 and 61 participants from Group 2 were included.

Because of the confound between the initial velocity and the acceleration of the ball (see Table 1), I also ran a generalized linear mixed model, which works by fitting a statistical model to the data to estimate the relationship between predictor variables and the outcome variable, and then comparing the predicted values generated by the model to the true values observed in the data to assess which cue participants relied upon most when making their judgments. In order to ascertain to what extent participants used the acceleration of the object relative to its initial velocity to make their judgments, I opted for model fit comparisons. For this purpose, I relied on the small amount of variability that was not shared between acceleration and initial target velocities, taking advantage of the fact that there were 4 different transit times in this study.

While initial velocity and acceleration were correlated with an R^2 of about 0.9, this leaves a non-negligible share of variation that was unique to acceleration and velocity, respectively. And given the large number of participants (combined both groups, 117 participants for Up and Down conditions, 118 participants for Left and Right conditions after removing the outliers) and with it, the high statistical power, I could leverage this small part of non-shared variability to determine which of the two sources of information they preferred. This model fit-based process has been used in at least one other study conducted to determine which cues participants used to make judgments about accelerations (Jörges et al., 2018). Following the approach laid out by Moscatelli et al. (2012), I fitted four generalized linear mixed models with logit link functions using the lme4 package for R (R Core Team, 2017). For all models, I set the participants' response on any given trial as dependent variable, random slopes for the motion direction as well as random intercepts per participant as random effects and the motion direction as fixed effect:

Response ~ Direction + (Direction|Participant) ……..…………………………………..[2]

This was the full structure of the first model ("Baseline Model"). I also fitted a model ("Full Model") that, additionally, had both initial velocity and acceleration as fixed effects:

Response ~ Acceleration + Initial Velocity + Direction + (Direction|Participant) …………….[3]

I further fitted an acceleration-only model:

Response ~ Acceleration + Direction + (Direction|Participant) ………………………..…….[4]

And a velocity-only model:

Response ~ Initial Velocity + Direction + (Direction|Participant) ……………………………[5]

I then compared the four models using model fit indicators (AIC, BIC, log-likelihood) as implemented in the anova() function from Base R.

3.0. Results

3.1. ANOVA Analysis

I ran separate within-participant ANOVAs for the two sets of participants, one set who performed the experiment for the 1.0 and 1.5 s transit times, the other for the 1.25 and 1.75 s transit times. I tested for sphericity to assess whether the variances of the differences between all possible pairs of related groups were equal and found that the assumption of sphericity was not violated. Separate ANOVAs were conducted for Down versus Up and Left versus Right in order to obtain a direct comparison between the two members of each motion direction orientation.

The ANOVA results are shown in Table 2. I adopted the $p < .025$ rather than $p < .05$ criterion for significance as a Bonferroni correction for performing statistical analyses on two separate transit times.

This table indicates that there is a significant difference in judgement precision between upward and downward motion for both the 1.0 s and 1.5 s group ($F(1,58) = 9.84$; $p = .0027$), and the 1.25 s and 1.75 group ($F(1,57) = 23.3$; $p < .0001$). However, there is no significant difference between perception of rightward and leftward motion for both the 1.0 s and 1.5 s group ($F(1,56) = 3.52$; $p = .07$), and the 1.25 s and 1.75 group ($F(1,60) = 22.5$; $p = .12$).

		Transit Time (s)	
		1.0, 1.5	1.25, 1.75
PSCV Comparisons	Down vs Up	F(1,58) = 9.84; *p* = .0027 ***	F(1,57) = 23.3; *p* < .0001 ***
	N	59	58
	Left vs Right	F(1,56) = 3.52; p = .07 ns	F(1,60) = 22.5; p = .12 ns
	N	57	61
Slope Comparisons	Down vs Up	F(1,58) = 4.78; p = .033 ns	F(1,57) = 0.0077; p = .931 ns
	N	59	58
	Left vs Right	F(1,56) = 3.167; p = .081 ns	F(1,60) = 0.37; p = .55 ns
	N	57	61

Table 2: PSCV and slope p values for significance for direction of motion differences. N = number of participants; ns = non-significant at the p < .025 criterion. The p-values for other direction pair comparisons are not shown but were all non-significant.

Figure 3 shows PSCVs (A and B) and psychometric function slopes (C and D) for Up versus Down (A and C) and Left versus Right (B and D). The figure shows that PSCVs varied with the ball's transit time, with faster transit times evoking more "acceleration" responses . This is indicative of a bias for "fast = accelerating." However, the bias I am primarily interested in here is that between Down and Up and for this comparison it is the relative positions of the PSCVs for Down and Up that is important. As my statistical analyses above confirm, for each transit time, Figure 3a shows that PSCVs for Down are relatively displaced towards acceleration (meaning they chose deceleration more when the ball was going down) compared to those for Up. No such difference can be seen for Left versus Right (Figure 3b).

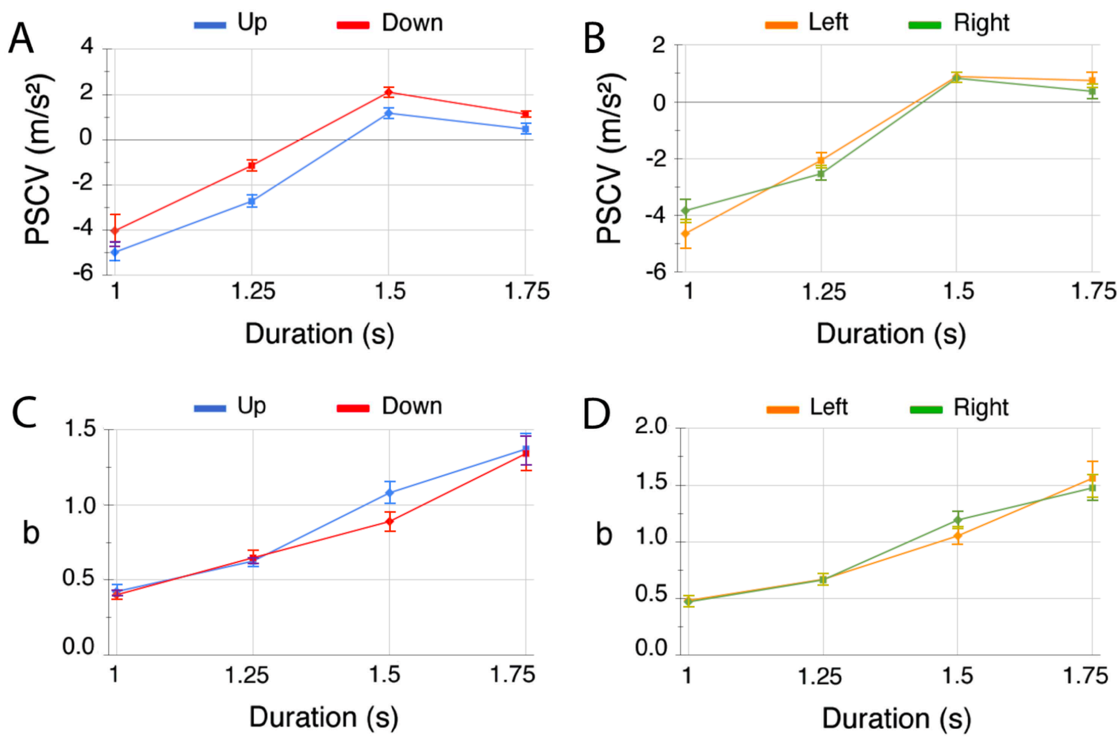

Figure 3: Mean PSCVs and psychometric function slopes b as a function of transit time and motion direction. A = Up/Down PSCVs; B = Left/Right PSCVs; C = Up/Down slopes; D = Left/Right slopes. Error bars represent standard errors.

As discussed earlier, biases are different from sensitivities. But could the results nevertheless be a byproduct of a sensitivity difference between Down and Up? Sensitivity is given by the slope parameter 'b' in the fitted psychometric functions. As I confirmed statistically above, Figure 3c and 3d shows no systematic differences in sensitivity between Down and Up or between Left and Right. Means and standard errors shown in Figure 3 are provided in Table 3.

	Direction	Transit time (s)			
		1.0	1.25	1.5	1.75
PSCVs	Down	−4.04 ± 0.57	−1.15 ± 0.36	2.10 ± 0.29	1.13 ± 0.15
	Up	−4.99 ± 0.49	−2.73 ± 0.41	1.17 ± 0.33	0.47 ± 0.31
	Left	−4.65 ± 0.47	−2.07 ± 0.29	0.89 ± 0.22	0.75 ± 0.27
	Right	−3.84 ± 0.44	−2.54 ± 0.30	0.83 ± 0.16	0.37 ± 0.39
Slopes	Down	0.401 ± 0.030	0.648 ± 0.057	0.89 ± 0.084	1.343 ± 0.133
	Up	0.423 ± 0.042	0.626 ± 0.061	1.081 ± 0.084	1.373 ± 0.112
	Left	0.481 ± 0.04	0.668 ± 0.058	1.052 ± 0.077	1.560 ± 0.162
	Right	0.469 ± 0.031	0.663 ± 0.054	1.192 ± 0.086	1.475 ± 0.124

Table 3: Mean PSCVs ($m \cdot s^{-2}$) with standard errors (SEs) and mean slopes with SEs for the data points shown in Figure 3.

3.2 Generalized Mixed Model Analysis

The model fit indicators (AIC, BIC, log-likelihood) showed that all three more complex models (full model eq 3, acceleration-only model eq 4, velocity-only model eq 5) had better model fits than the Baseline model (eq 2) even after accounting for the additional parameters ($p < .0001$). Furthermore, the full model was significantly better than both the acceleration-only model ($p < .0001$) and the velocity-only model ($p < .0001$), indicating that participants relied both on acceleration and velocity information.

In order to compare the acceleration-only and velocity-only models, a model fit indicators (AIC, BIC, log-likelihood) was not necessary since both models had the same number of parameters. The Akaike information criterion (AIC) values, where a lower AIC indicates the better model, favored the acceleration model (AIC = 94,554) over the velocity model (AIC = 99,390), with a difference of 4,836. According to Burnham and Anderson (2002, 2004), an AIC difference of just 7 or more is significant. The dominance of the acceleration only model was also confirmed with a Bayesian information criterion (BIC) analysis (where smaller is also better) with a score of 94,693 for the acceleration only model and 99,529 for the velocity only model. Finally, a log-likelihood analysis (where this time, bigger is better) gave −47,262 for the acceleration-only model and −49,680 for the velocity-only model. Together these analyses constitute strong evidence that although both variables explained a significant amount of the variability, all model fit criteria favored the acceleration-only model when compared to an initial velocity-only model. That is, while participants did rely on both cues, they relied more on acceleration than on the initial velocity.

4.0. Discussion

4.1. General Discussion

Aristotle believed that falling objects fell at a constant velocity. My results support the idea that his belief may in part be due to a bias that acts to reduce the perceived magnitude of acceleration for falling objects, a bias that to my knowledge has never been revealed in previous studies of visual motion. I have revealed a novel bias difference between the perception of upwards and downwards motion in which downwards motion requires more acceleration than upwards motion to be judged as moving at constant velocity. That is, low levels of acceleration of a falling body appear as moving at a constant velocity.

As mentioned in the introduction, a recent study by Nguyen and van Buren (2023) found greater sensitivity to Up compared to Down, which would predict higher values of the slope parameter b for upwards motion in my study (Eq 1). My ANOVA analysis however revealed no significant differences in slopes either between Up and Down or between Left and Right. There are many differences in the experimental methods employed by Nguyen and van Buren (2023) and my study that could potentially account for the differences in sensitivities measured. Nguyen and van Buren (2023) presented only acceleration and constant speed trials, the former with just one value of acceleration (144 pix/s^2 on a computer monitor) and participants were required to indicate “acceleration” or “constant speed” on each trial. In my study, I presented a range of accelerations and decelerations with the participants’ task being to judge “accelerating” or “decelerating” on each trial. Perhaps the fact that in Nguyen & van Buren's study half the trials were constant speed and the other half just one value of acceleration served to sharpen participants’ sensitivities.

Nguyen and van Buren (2023) argue that the higher sensitivity they observed for Up versus Down was due to a visual prioritization of speed changes in the opposite direction to gravity, because such speed changes are indicative of the presence of animate forces. It does not follow however that greater sensitivity to Up than Down speed changes would lead one to expect the bias differences in Up and Down PSCVs found here.

One might suppose that participants would have responded “accelerating” relatively more often than “decelerating” to Down compared to Up on the grounds that they would have expected downwards-moving objects to accelerate and upwards-moving objects to decelerate. Indeed, much evidence supports such an expectation bias (reviewed by Nguyen & van Buren, 2023). However, such an expectation bias would predict the opposite of what I found; an expectation bias would predict that, to compensate for the bias, the Down PSCVs would lie to the left of the Up PSCVs on the deceleration-to-acceleration axis (in Fig 1) – but my data (Fig 3) are in the opposite direction to that with DOWN having a positive bias (to the right in the format of Fig 1). Therefore, it would appear that the perceptual bias revealed in my study overrides any such cognitively driven expectation bias.

Despite participants being explicitly instructed not to track the ball, I was not able to monitor their eye movements and an asymmetry between up and down eye tracking (Ke et al., 2013) could have inadvertently influenced my results. Future investigations should investigate and control specifically for such a possibility.

To focus my observer's attention on the movement of the ball, my experiments used a fixed distance (4m), fixed transition times (just two for each participant) and fixed average velocity (distance/time). This meant that although participants could not use distance or time to deduce the motion of the ball, there had to be a correlation between both the end velocity and the initial velocity of the ball and its acceleration. There is a suggestion in the literature that people are not very sensitive to visual acceleration (Watamaniuk & Heinen, 2003) and that they might instead be deducing the answer to the question “was it accelerating or decelerating?” from a comparison of the start or end velocities. My claim does not require a direct perception of acceleration – I remain neutral for the moment as to whether humans can or cannot detect visual acceleration directly – and instead claim, as stated in the title, that there is a visual bias for falling objects, one that is not present for sideways moving objects. However, the results from the general mixed modeling indicate that while participants did rely on both cues, they did rely significantly more on acceleration than on the initial velocity.

4.2. Limitations and Future Studies

There are some limitations in this study. Firstly, due to COVID-19 restrictions, the experiment was conducted online, which introduced potential uncertainties regarding participants' adherence to instructions and the quality of their engagement. Despite efforts to provide clear instructions and monitor participant responses, the absence of direct supervision does raise concerns about consistency in task progress and completion.

Additionally, the experiment was conducted in a two-dimensional (2D) environment, which may not fully capture the complexities of real-world spatial perception experienced in three-dimensional (3D) settings. This limitation highlights the need for future research to explore spatial perception in immersive 3D environments, potentially through virtual reality (VR) technology. Incorporating VR technology could offer a more ecologically valid approach, allowing for greater immersion and realism in spatial tasks, thus enhancing the generalizability and applicability of findings. It would also allow a better control and larger range of distances. By doing the experiment at much further simulated distances (such as throwing a highly visible large object off the top of a high cliff and viewed from a distance), longer transit times and larger changes in velocity during the movements could be created.

Moreover, although a definitive conclusion regarding the cause of the downward acceleration perception bias could not be reached in the present study, it seems likely that the observed results was due to our regular exposure of objects accelerating downwards and decelerating when thrown upwards. This lifelong experience may have led to the internalization of a gravity prior (Jörges & López-Moliner, 2017, 2020) although such a bias could actually be innate (Bliss et al., 2023). This internalized assumption would then underlie the bias I saw. For Left versus Right visual motion there is no regularly experienced differential amounts of acceleration or deceleration, hence I would not expect, nor do I find, a similar bias. In the future, more studies should be conducted to see whether this effect is present in other contexts - such as if participants are tested in the microgravity of space or in a simulated underwater environment.

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