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Evidence of weight-based representations of gravitational motion

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Abstract

A hypothesis gaining increasing popularity is that laypeople's representations of physical phenomena might be driven by internalized physical laws. In three experiments, we tested if such hypothesis holds true for the representation of gravitational motion. Participants were presented with realistic, real-scale virtual spheres falling vertically downward from about 2 m high. The spheres appeared to be made of either polystyrene or wood. In Experiment 1, participants adjusted the falling motion pattern until it appeared to be natural. In Experiment 2, they compared the perceived naturalness of vertical free falls in a vacuum with the perceived naturalness of more realistic falls characterized by the presence of air drag. In Experiment 3, they estimated the position of the sphere after a variable interval of time from the beginning of the fall. Inconsistently with predictions from physics, results showed that representations of gravitational motion were strongly affected by the implied masses of the falling objects and did not account for air drag. This provides support for the hypothesis of weight-based heuristic representations of gravitational motion against the hypothesis of the internalization of physical laws.

Keywords

Intuitive physics; Gravitational motion; Heuristics; Internalization; Bayesian models.

Public significance statements

1) This study explores how an everyday life event like the free vertical fall of an object is represented by our cognitive system. We test two opposing hypotheses, namely that either our representations of physical events are consistent with the corresponding physical laws or that they are based on sub-optimal heuristics.

2) The results provide support for the hypothesis that our representations of vertical free fall are driven by a sub-optimal weight-speed heuristic by which, inconsistently with predictions from physics, relatively heavy objects fall much faster than relatively light objects.

3) The results of the present study suggest that our representations of physical phenomena are not generally consistent with physical laws.

Evidence of weight-based representations of gravitational motion

1. Introduction

Imagine an animated pendulum swinging back and forth. Would you be able to tell whether its period is the physically correct one or not? If the rope of the pendulum were suddenly severed, would you be able to predict the weight's trajectory? Questions like these comprise the focus of studies in intuitive physics, which investigates people's intuitive understanding of physical phenomena (for recent reviews see Kubricht et al., 2017; Vicovaro, 2021). Studies in intuitive physics have typically explored relatively simple mechanical events such as projectile motion, collisions, and descents along inclined planes. It would be reasonable to presume that, because of the repeated exposition to real life physical phenomena, people might have developed accurate intuitive knowledge of physical laws. Yet early studies showed that this is not always the case (Bozzi, 1958; 1959; McCloskey et al., 1980; Shanon, 1976). For instance, the period of a pendulum that is perceived as 'most natural' by observers is longer than the correct one (Bozzi, 1958; Pittenger, 1990). Moreover, about one third of the participants in a study by Caramazza et al. (1981) believed that, if the rope of the pendulum is severed while the weight is at the apex of its trajectory (i.e., just before the swing direction changes), then the weight would fall with a parabolic trajectory rather than with the physically correct straight-down trajectory.

Better understanding of intuitive physics would improve the teaching of physics by providing valuable insights on how to correct students' most common misconceptions (McDermott, 1991). As emphasized by Carey (1986) and McDermott (1991) among others, students do not automatically update their misconceptions about mechanical events when confronted by the physics teachers with new notions. On the contrary, they typically distort the new notions to make them consistent with their own old beliefs.

Intuitive physics has also applications in the field of computer graphics. Through the exploration of the observer sensitivity to violations of the laws of mechanics, animators can determine the minimum level of accuracy that simulated physics engines require to create perceptually realistic videogames and animations. For instance, if empirical data show that observers are not particularly sensitive to violations of some physical laws of mechanics, then animators can save on the computational costs of reproducing exact Newtonian mechanics (Barzel et al., 1996; Reitsma & O'Sullivan, 2009; Vicovaro et al., 2014).

The study of intuitive physics has also theoretical significance as it can shed light on the processes underlying cognitive representations of the world. In the following subsections, two theoretical perspectives on intuitive physics are introduced. The 'heuristic perspective' postulates that intuitive physics relies on sub-optimal heuristics and thus focuses on the discrepancies between intuitive and scientific physics and on their origins. In contrast, the 'internalization perspective' which has recently gained increasing popularity postulates that intuitive physics is actually based on internalized physical laws, thus pushing forward the hypothesis of a substantial similarity between intuitive physics and physical laws. After providing an outline of these perspectives on intuitive physics, the remainder of the article focuses on the study of intuitive physics of gravitational motion, which refers to the motion of objects under the influence of gravitational acceleration.

1.1 The heuristic perspective

In their seminal works on people's intuitive understanding of elementary physics problems such as the motion of projectiles released by moving carriers or exiting from curvilinear tubes, McCloskey and colleagues (Kaiser, McCloskey, & Proffitt, 1986; McCloskey, 1983; McCloskey et al., 1980; McCloskey & Kohl, 1983) suggested that participants' errors in intuitive physics tasks are not consequences of random responses or of ignorance of the laws of motion. Rather, they result from the application of a consistent system of beliefs that is reminiscent of Medieval impetus theory. According to impetus theory, an object moves when an external force imparts an impetus to it. Impetus has a definite direction and it gradually dissipates, therefore an object will continue moving in the direction of the impetus until either the impetus vanishes or other external forces intervene. Some scholars have criticized McCloskey's analogy between intuitive physics and Medieval impetus theory, suggesting that intuitive physics is a set of relatively isolated explanations for specific physical phenomena, rather than a consistent system of beliefs resembling an ancient theory of mechanics (diSessa, 1993; Yates et al., 1988). In support of the latter hypothesis, some studies have shown that participants' predictions about the motion of objects can, depending on the context, exhibit more consistency with impetus theory, Aristotelian physics, or Newtonian physics (Clement, 1982; Cooke & Breedin, 1994).

As to the possible origins of misconceptions about mechanical events, McCloskey and Kohl (1983) theorized that intuitive physics is based on the generalization of perceptual experiences with specific 'prototypical' physical phenomena with which laypeople are familiar (see also Yates et al., 1988). For instance, laypeople believe that an object rolling inside a curvilinear tube would follow a curvilinear trajectory when exiting the tube rather than a straight path according to Newtonian physics (Kaiser, McCloskey, & Proffitt, 1986, 1986; McCloskey et al., 1980; McCloskey & Kohl, 1983). McCloskey and Kohl (1983) conjectured that this misconception might arise from the overgeneralization of everyday life experience with the motion of wheels. A wheel set in motion continues to rotate for some time until it eventually stops. Therefore, if laypeople relied on such prototypical event to make predictions on curvilinear motion in general, they would incorrectly presume that curvilinear motion perpetuates itself even in absence of external forces.

Several misconceptions about physical phenomena have been explained in terms of the overgeneralization of perceptual-motor experience with everyday life physical phenomena. For instance, suppose that participants are presented with a scene of a moving object *A* that strikes a stationary object *B* that starts moving immediately after the collision. White (2007) found that when participants are asked to rate the force exerted by *A* on *B* and by *B* on *A*, they consistently underestimate or ignore the force exerted by *B* on *A*. This is at odds with Newton's third law of dynamics, by which the module of the force exerted by *B* on *A* is the same as that of the force exerted by *A* on *B*. White (2006; 2007; 2012) suggested that this bias would stem from perceptual-motor schemes based on everyday life experience with physical objects (see also diSessa, 1993). For instance, when pushing an object on a flat surface (e.g., a cup on a table), we are aware of the force that our hand exerts on the cup. However, when the result of the planned action (i.e., the cup moving with speed *v*) is consistent with the original motor plan (i.e., pushing the cup with speed *v*), the sensorimotor feedback coming from the mechanoreceptors is attenuated, thus reducing our awareness of the force exerted by the cup on our hand (see White, 2012). In a similar vein, Hecht (2001) argued that intuitive physics might be based on heuristics involving the externalization of body dynamics. For instance, in the case of a thrown ball, the hand of the thrower typically accelerates until the ball is released, and then the ball starts decelerating immediately after the release. However, laypeople believe that the ball continues to accelerate after the release (Hecht & Bertamini, 2000). According to Hecht (2001) participants are extending the dynamics of the hand (i.e., acceleration) to the motion of the ball.

1.2 The internalization perspective

In contrast with the heuristic perspective, the idea that internalized physical laws might drive laypeople's representations of physical phenomena has recently gained increasing popularity. For instance, it has been suggested that the extrapolation of projectile trajectory is driven by an internalized representation of gravitational acceleration (i.e., the '1*g* model', see Bosco et al., 2012; Jörges & López-Moliner, 2019; 2020; McIntyre et al., 2001; Zago et al. 2010; Zago et al., 2008). Battaglia et al. (2013) have further pushed forward the hypothesis that laypeople's representations of physical phenomena are generated through mental simulations of the possible future states of these phenomena. These mental simulations can be described in terms of a Bayesian model that integrates perceptual information with internalized Newtonian principles (see also Kubricht et al., 2017; Ullman et al., 2017). Empirical studies have shown that the predictions of these models fit participants' responses in various physical domains, such as ballistic motion (Smith et al., 2013), liquid dynamics (Bates et al., 2015), collision dynamics (Gerstenberg et al., 2012; Sanborn et al., 2013; Smith & Vul, 2013), and the stability of towers of simulated 3D blocks (Battaglia et al., 2013; Hamrick et al., 2011). In a recent study, Lau and Brady (2020) have found that colliding objects were easier to track when their deflection angles were consistent with the Newtonian laws of collisions compared to when they were not consistent with these laws, thus suggesting that attentional processes might also be driven by internalized Newtonian principles.

According to the internalization perspective, Bayesian processes relying on internalized Newtonian principles would have evolved in order to provide rapid inferences about real life events. Participants' responses are then expected to be accurate (i.e., consistent with the predictions from physical laws) when the simulated phenomena presented in intuitive physics experiments are similar to the corresponding real phenomena (Hamrick et al., 2011; Kubricht et al., 2017; Ullman et al., 2017). On the contrary, Bayesian models may not provide accurate predictions in case of static, schematic, and unrealistic representations of the phenomena. Coherently with this hypothesis, participants show better performance in intuitive physics tasks involving concrete and familiar physical events, rather than in tasks involving the abstract representation of the same events (Kaiser, Jonides, & Alexander, 1986; Masin et al., 2014). Moreover, participants provide more accurate judgements when they are presented with dynamic simulations of physical phenomena, compared to when they are presented with static and schematic depictions of the same phenomena (Frick et al., 2005; Hecht & Bertamini, 2000; Huber & Krist, 2004; Kaiser et al., 1985; Kaiser et al., 1992; Shanon, 1976; Smith et al., 2013). Similarly, participants show better performance in tasks involving motor interactions with physical objects, rather than in tasks involving abstract cognitive predictions about the behavior of the same objects (Huber et al., 2003; Krist et al., 1993; Lacquaniti & Maioli, 1989; Zago & Lacquaniti, 2005; Schwartz & Black, 1999). Overall, these findings provide support to the hypothesis that laypeople can make accurate predictions about physical phenomena only in ecologically valid simulated scenarios.

A detailed discussion of the extents and limits of the internalization perspective goes beyond the scope of the present work. Nonetheless, an important merit of this perspective is that it emphasizes the importance of the realism of the stimuli in intuitive physics experiments. Although the main aim of intuitive physics studies is to investigate laypeople’s representations of physical phenomena, the stimuli used in intuitive physics experiments often differ from real life phenomena in several respects. First, and most obviously, they are typically small-scale simulations suitable for presentation on a computer screen. Second, the ‘objects’ involved are usually ‘featureless’ two-dimensional shapes, rather than 3D objects characterized by definite properties such as stiffness, elasticity, and mass. Third, simulations are typically based on simplified Newtonian physics that does not account, e.g., for friction. The extent to which these simplifications may affect participants’ performance in intuitive physics tasks should be a primary source of concern for researchers in the field of intuitive physics. To make an illustrative example, since Michotte’s (1946/1963) seminal study on the perception of causality, the intuitive physics of collisions has been mainly studied using simple animations involving immaterial shapes moving in one or two dimensions (e.g., Gestenberg et al., 2012; Lau & Brady, 2020; Runeson & Vedeler, 1993; Sanborn et al., 2013; Smith & Vul, 2013; Vicovaro et al., 2020; White, 2007). Only few studies have attempted to increase the realism of simulated collisions, for instance by using 3D spheres made of definite simulated materials (Vicovaro, 2018;

Vicovaro & Burigana, 2016) or by mimicking the effects of friction and rotation on the collision behavior of the stimuli (Meding et al., 2020; Reitsma & O'Sullivan, 2009). The results of these studies suggest that the realism of the stimuli has a substantial influence on subjective judgments of the naturalness of collisions.

1.3 The physics of gravitational motion

Gravity is a ubiquitous physical force that affects both the external and the internal structure of all living creatures and inanimate objects. On Earth, all objects are subject to a standard downward acceleration that is tantamount to $1g \approx 9.81\ m/s^2$, and that is why gravitational motion is perhaps one of the most frequent physical phenomena occurring in our everyday life. Consistently with the internalization perspective, it can be predicted that laypeople should have an accurate representation of gravitational motion.

The intuitive physics of gravitational motion has been widely explored by means of abstract reasoning tasks. Participants were typically required to predict the unseen motion of a hypothetically falling object by answering questions like "How long will it take an object weighing m kg to reach the ground if it falls from s m high?", or "How fast will an object weighing m kg will arrive at the end of a descent along a plane inclined by α degrees?" (see, e.g., Champagne et al., 1980; Halloun & Hestenes, 1985; Karpp & Anderson, 1997; Oberle et al., 2005; Proffitt et al., 1990; Sequeira & Leite, 1991; Shanon, 1976; Vicovaro, 2014; Whitaker, 1983). The results of these studies consistently indicate that laypeople, and in some cases even university physics students (Sequeira & Leite, 1991), believe that heavier objects fall to the ground faster than lighter objects. This 'mass-speed belief' (Rohrer, 2002) is wrong in the framework of Newtonian physics. Indeed, in a vacuum (i.e., in the absence of friction) all objects fall toward the center of gravitational attraction with fixed uniform acceleration irrespectively of their mass. The distance travelled by the object is given by the following motion equation:

$$S(t; a) = 0.5 \times at^2 \tag{1}$$

where $S(t; a)$ is the position of the object as a function of time (t) and acceleration (a; on Earth, a=g). Equation 1 means that, if the effects of air resistance are absent or negligible, then the material properties of objects like mass, size and shape do not have any influence on the falling motion. Indeed, on the Moon, where the effects of air resistance are negligible, a hammer and a feather fall with the same uniform acceleration (see https://www.youtube.com/watch?v=KDp1tiUsZw8). On Earth, however, the effects of air resistance are not negligible. This raises the question of whether Equation 1 can be considered a good approximation of gravitational motion in a terrestrial environment or not. In this regard, school physics textbooks tell us that, when he was still a young mathematics teacher, Galileo went on the top of the leaning tower of Pisa and dropped objects varying in mass and size, showing to the astonished bystanders that they all fell at the same rate. Unfortunately, this story is likely to be false or at least incorrectly reported (Darling, 2006). In an actual experiment conducted by Giovanni Battista Riccioli in the 16th century (see Graney, 2012), two clay spheres of identical size but different mass (i.e., one sphere was twice as heavy as the other) were dropped simultaneously from the top of the Asinelli tower in Bologna (about 85m high). The heavy sphere touched the ground about one second earlier than the light sphere, which indicates a small but non-negligible effect of mass on falling speed. The vertical distance travelled by an object toward the center of a gravitational attraction in presence of an air quadratic drag is given by the following motion equation:

$$S(t;m,a) \;=\; \frac{2}{C_d \times A} \times \frac{m}{\rho} \times log(cosh(\frac{\sqrt{\frac{a\rho}{m}}t}{\sqrt{\frac{2}{C_d \times A}}})), \qquad (2)$$

where $S(t;m,a)$ is the object position as a function of time (*t*), acceleration (a) and object’s mass (*m*), C_d is the drag coefficient, *A* is the object’s cross-sectional area, and ρ is the density of the medium. On Earth, a = g = 9.80665 ≈ 9.81 m/s^2, ρ = 1.2047 kg/m^3 for air at a standard temperature of 20 °C, while C_d = 0.47 for a smooth sphere. Figure 1 provides a depiction of the motion patterns of two spheres falling either in a vacuum (Equation 1) or on Earth (Equation 2). It is assumed that both spheres have a diameter of 5 cm (A = .0019625 m^2 in Equation 2), and that one sphere is made of wood (m = .055 kg) and the other is made of polystyrene (m = .005 kg). The position of the spheres is represented at every .05 s interval, in the time range between zero and one second. As shown in Figure 1, whereas in a vacuum the heavy and the light sphere travel the same distance in the same time, on Earth the heavy sphere travels a longer distance compared to the lighter sphere. As illustrated by this example, the mass-speed belief should not be simply dismissed as a misconception, because in several circumstances the mass of objects actually exerts a non-negligible influence on their falling motion (see also Oberle et al., 2005).

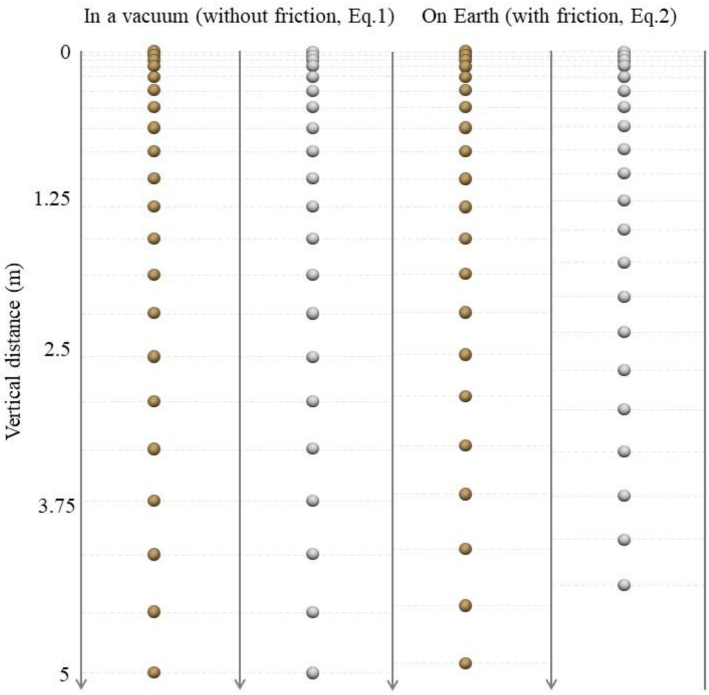

Figure 1. Illustrative representation of the vertical fall according to Equation 1 (left) and Equation 2 (right) for the wooden (*m* = .055 kg) and polystyrene (*m* = .005 kg) sphere. Gray dotted lines represent the sphere position every .05 s along its vertical trajectory between the interval .0 – 1.0 s. The vertical fall with no air friction (Eq.1) is independent of the sphere's material, whereas when air resistance is considered the average falling speed of the wooden sphere is higher than that of the polystyrene sphere.

1.4 A possible internalized representation of gravitational motion?

According to the internalization perspective, internalization of physical laws serves the purpose of generating accurate predictions about physical phenomena in real life situations. Therefore, the physical laws that are most likely to be internalized might not be those describing the behavior of objects in an idealized frictionless Newtonian environment like in Equation 1, but rather those underlying the behavior of objects in real life situations like in Equation 2 (Hamrick et al., 2011; Kubricht et al., 2017). If laypeople had an internalized representation of Equation 2, it would not be surprising if they believed that heavier objects tend to fall faster than lighter ones, because this is actually the case according to Equation 2. In other words, although the mass-speed belief has been often referred to as an example of laypeople's poor understanding of physics (Champagne et al., 1980; Bozzi, 1959; Rohrer, 2002; Whitaker, 1983), taken alone this belief might not constitute definitive proof against the internalization of physical laws. Testing the internalization of Equation 2 would require a careful quantitative comparison between the magnitude of the effects of mass on subjective representations of vertical fall, and the magnitude of the effects of mass on falling speed as predicted by Equation 2. In the light of the fact that gravitational motion is a common real life phenomenon, this comparison would be theoretically meaningful for the debate over the internalization hypothesis.

Previous studies suggested that an internalized representation of gravitational acceleration assists participants in the manual interception of objects falling vertically downward (Lacquaniti & Maioli, 1989; McIntyre et al., 2001; Zago et al., 2008; 2010; but see Baurès et al., 2007; Zhao & Warren, 2015). However, according to Zago and Lacquaniti (2005) only the motor system would rely on an internalized representation of gravity, whereas perceptual and cognitive representations of gravitational motion would be based on heuristic processes. Nevertheless, according to recent conceptualizations of the internalization hypothesis (Battaglia et al., 2013; Kubricht et al., 2017; Sanborn et al., 2013; Ullman et al., 2017), internalized representations of physical laws would drive not only action, but also perception and the cognitive representations of physical phenomena (see also subsection 1.2).

Existing literature does not provide conclusive evidence as to whether laypeople have a correct perceptual representation of terrestrial gravitational acceleration, that is, whether or not they can discriminate correct from incorrect gravitational motion at a perceptual level. In his pioneering study, Bozzi (1959) presented participants with small-scale, schematic two-dimensional animations of objects (i.e., rectangles) descending along an inclined plane (i.e., a triangle). He found that the motion pattern that was perceived as the most natural was an initial brief acceleration followed by constant velocity, which corresponds to a constant velocity motion at a perceptual level. These results appear to indicate a clear discrepancy between the physically correct gravitational motion captured by Equation 2 (i.e., accelerated motion until a terminal constant velocity is reached) and the motion pattern that was perceived as most natural by participants (i.e., constant velocity motion). Moreover, Bozzi (1959) found that the falling speed that was perceived as most natural for a relatively large square was higher than the speed perceived as most natural for a relatively small square, suggesting a possible effect of the object implied mass on the perceived naturalness of the falling speed. A few years later, Shanon (1976) presented participants with edited slow-motion videos of real balls falling vertically downwards. Inconsistently with the results of Bozzi (1959), he found a preference for uniform acceleration over constant velocity; Shanon (1976) did not manipulate the implied masses of the falling objects. Due to their pioneering character, the studies by Bozzi (1959) and Shanon (1976) inevitably suffer from some methodological limits and from a lack of realism of the experimental stimuli, which makes the results of these studies hardly generalizable. More recently, Twardy and Bingham (2002) presented participants with animations showing a sphere falling to the ground from high above and bouncing on the ground multiple times. The sphere's motion took place in a simulated small-scale 3D environment in which effects of air resistance were also accounted for. The animations could present either a physically correct value of simulated gravitational acceleration (i.e., $1g$) or a gradual increase/decrease of simulated gravitational acceleration (i.e., the simulated gravitational acceleration gradually increased or decreased with time). Participants were asked to rate the perceived naturalness of each animation. Results showed that animations showing gradual decreases of gravitational acceleration were perceived to be less natural than those showing correct acceleration or gradual increases of acceleration, whereas no difference in perceived naturalness emerged between the latter two types of animations. It is however worth noting that, in Twardy and Bingham's (2002) experiment, the naturalness judgments might have been based on the relative heights of the sphere's bounces rather than on its falling motion. Moreover, the falling object was a simulated featureless sphere the hypothetical weight of which was only communicated verbally to the participants. This makes it hard to tell if participants had an accurate representation of the influence of the mass of the sphere on its falling motion. In an attempt to overcome the limits of realism of the stimuli used in previous studies, in a recent study Vicovaro et al. (2019) presented participants with real-scale simulations of material spheres falling vertically downward. The simulated material of the spheres could be either wood or polystyrene, and the spheres could fall either at a constant velocity or with uniform acceleration. Participants were asked to rate the perceived naturalness of each simulated fall. Results showed a strong interaction between the implied mass of the sphere and the values of acceleration or velocity that were perceived to be natural for that sphere, in line with a mass-speed belief. Results also showed a slight preference for uniformly accelerated motion over constant velocity motion. However, effects of air resistance were not simulated, therefore none of the simulated falls presented to the participants was physically correct. Moreover, due to the subjective use of rating scales, the naturalness ratings could not provide a precise measure of the physical parameters (e.g., acceleration).

The intuitive physics of gravitational motion has also been explored through more 'indirect' tasks in which participants were asked to provide judgments about specific stimulus properties in the context of gravitational motion. For instance, Hecht et al. (1996) presented participants with real-scale simulations of target balls moving vertically upwards and then downwards under the effects of g. Participants were tasked with estimating the size of the target ball and its distance from their viewpoint. If a target moves under the effects of g, then its motion profile uniquely specifies its size and its distance from the observer. Therefore, if participants had a correct internalized knowledge of gravitational acceleration and they were sensitive to the optical information provided by accelerated motion, then in principle they could provide accurate estimates of size and distance. However, the results showed that responses were mostly based on the average velocity of the target, which is a suboptimal visual cue, rather than on the full optical information provided by the acceleration profile of the target. In a more recent study, Jörges et al. (2018) showed to participants virtual animations of a tennis ball moving towards them with a parabolic trajectory. On each trial, participants were tasked with indicating which motion, between a standard and a test parabola, was produced by the stronger gravity. The gravitational acceleration underlying each parabola was uniquely specified by a combination of optical variables (i.e., rate of change of elevation angle and visual angle). If participants were sensitive to these variables, then in principle they could make accurate estimations of gravitational acceleration. However, the results showed that a difference of 13% up to more than 30% between the gravity values underlying the standard and the test parabola was required for an accurate discrimination. Results of these studies (i.e., Hecht et al., 1996; Jörges et al., 2018) suggest that individuals are not particularly sensitive to the optical cues that would allow them to provide accurate judgments in the context of gravitational motion. However, a noteworthy feature of the stimuli used in these studies is that the effects of air resistance were not accounted for. Therefore, it cannot be a priori excluded that the observed sub-optimal levels of performance could be due, at least partially, to the level of realism of the stimuli.

1.5 Experiments overview

As discussed above, realism of the stimuli is an outstanding problem in intuitive physics studies and systematic biases in perceptual judgements of physical phenomena may be due to a lack of realism rather than to poor intuitive knowledge of physics (Battaglia et al., 2013; Hamrick et al., 2011; Kubricht et al., 2017). In the light of this problem, the general aim of the current sets of experiments is to provide a detailed picture of laypeople's perceptual and cognitive representations of gravitational motion using realistic stimuli. In three experiments, participants were presented with real-scale simulations of realistic wood or polystyrene spheres falling vertically downward (see Figure 2). The simulated spheres were perceptually similar to real wood and polystyrene spheres that participants could manipulate at the beginning of each experiment. The two real spheres weighed respectively .055 kg and .005 kg. The falling motion patterns of these spheres, either in a vacuum or on Earth, are represented in Figure 1.

In Experiment 1, participants were asked to adjust the falling speed of the simulated spheres in three different scenarios. These scenarios differed along two main dimensions: in terms (1) of the presence or absence of the simulated effects of air drag, and (2) of the physical parameter of the falling motion that was actually adjusted by the participants, which could be either the gravitational acceleration a or the density ρ of the medium. If participants relied on an internalized representation of Equation 2 then the values of the to-be-adjusted physical parameters giving rise to perceptually natural falls should be substantially consistent with the corresponding physical values. In Experiment 2, we used a 2-AFC paradigm to explore if participants showed a systematic preference for realistic simulated falls (i.e., with the simulated effects of air resistance), over less realistic simulated falls in a vacuum. Lastly, Experiment 3 aimed at mapping the trajectory of the imagined vertical falls of simulated wooden and polystyrene spheres. Participants had to estimate, at different time intervals after the starting of the fall, the position of the virtual wooden or polystyrene sphere whose trajectory was hidden by an occluder. Results allowed us to test the hypothesis that mental simulations of gravitational motion might be driven by internalized physical laws.

All procedures used in the three experiments had been approved by the Ethics Committee of the Department of General Psychology of the University of Padova (protocol number 3342). The experiments were conducted in October-December 2019, before the Covid 19 pandemic in Italy.

2. Experiment 1

In this experiment participants were required to adjust, using two keys on a keyboard, the vertical falling motion of a real-sized virtual sphere projected on a large screen, until the aforementioned falling motion was perceived as ‘natural’, i.e., coherent with the real falling motion of a corresponding physical sphere. The virtual sphere reproduced either a real sphere made of wood or one made of polystyrene.

2.1 Sample Size

In order to determine the sample size, we focused on the hypothesis considered the most important, that is, the presence of an effect of the object’s simulated material (i.e., weight) on the physical parameters that correspond to a perceptually natural fall. In a previous study, Vicovaro et al. (2019) found a strong interaction effect between the implied weight of a simulated sphere and the magnitude of downward acceleration/velocity that was perceived as most natural for the vertical fall of that sphere (i.e., $\eta_G^2 = 0.17$ with a sample size of 30). Differently from that study, here participants did not rate the naturalness of the falling motion, but they directly adjusted the physical parameters of the fall. The hypothesis of an effect of simulated material (i.e., implied weight) on the to-be-adjusted parameters can be tested through paired-sample one-tailed *t*-tests. Assuming at least a medium effect size of implied weight on the estimated values of the physical parameters (i.e., $d = .5$), and assuming $\alpha = .05$ and $\beta = .80$, a power analysis estimated a sample size of 26.14. In order to remain on the safe side, we decided to test 30 participants.

2.2 Participants

Thirty students from the University of Padova (13 males, mean age = 24.37 years, SD = 2.64 years) voluntarily took part in both Experiment 1 and Experiment 2. Experiment 2 took place at least two days after Experiment 1, and at the end of Experiment 2 the participants received 10 € of compensation for participation. On average, participants had studied physics at school for 3.5 years (SD = 1.44 years). All of them were naive to the purpose of the experiment and reported normal or corrected-to-normal visual acuity.

2.3 Apparatus

The participants sat in a dimly lit room at 340 cm distance from a white vertical wall, with a keyboard placed on their knees. Viewing was binocular, stimuli were generated with MATLAB and Psychtoolbox (Brainard, 1997; Pelli, 1997) and displayed on the wall using a Canon lv7275 projector. The projected screen was 197.1 cm ✕ 156.6 cm (1280 ✕ 1024 pixels resolution). The refresh rate was set at 60 Hz. The vertical distance between the lower limit of the screen and the floor of the room was 65.1 cm, while the distance between the upper limit of the screen and the ceiling of the room was 50.3 cm (see Figure 2).

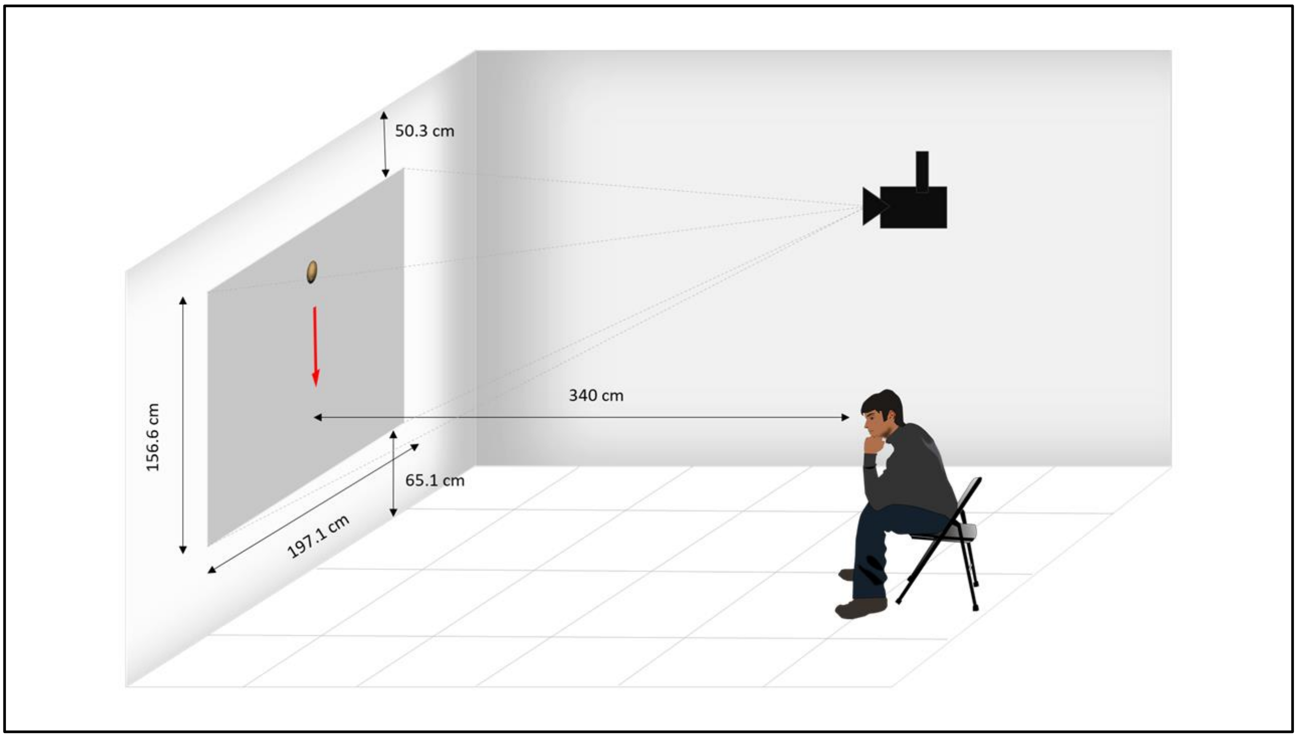

Figure 2. Representation of the experimental setup, with black arrows and numbers indicating the relevant distances. The red vertical arrow on the projected screen has been added for illustrative purposes, it indicates the motion direction of the sphere.

2.4 Stimuli and Procedure

Before starting the experiment, participants read and signed an informed consent form. Written instructions informed the participants that they would be presented with real wood and polystyrene spheres that they could touch and manipulate with both hands. They were then informed that, after giving the spheres back to the experimenter, virtual wooden or polystyrene spheres identical to those they had just manipulated would have appeared on the vertical wall in front of them. They were told that one sphere at a time would have been presented, and that at some point the sphere would have started falling vertically downward. Their task was to adjust the falling motion of the sphere until it appeared to be natural, that is, consistent with the falling motion of the corresponding real sphere falling from that height. They were instructed to press ‘Z’ to decrease and ‘M’ to increase the falling speed of the sphere, and to press ‘Q’ when the motion of the sphere looked to be natural. Note that participants did not actually manipulate speed but either acceleration or density of the medium (see below), however ‘speed’ is a simple term that made the task clearly understandable to them.

Participants were then presented with the two real spheres of 5 cm diameter made of wood (m = .055 kg) and polystyrene (m = .005 kg), and were left free to manipulate them for about 30 sec. After that, the experimenter took the spheres back, placed the keyboard on the participant’s legs, and then the experiment started. On each trial, a virtual wooden or polystyrene sphere was presented, centered 5.5 cm below the upper limit of the screen (see Figure 2). The virtual spheres had the same size as the real spheres, and their simulated texture was chosen so to make them as similar as possible to the real spheres. After a time interval randomly sampled from a normal distribution with mean 1 s and standard deviation .5 s, the virtual sphere started falling vertically downward, until it disappeared beyond the lower limit of the screen. After the participant’s response and a 50 msec blank screen, a new trial started in which the physical parameters of the falling motion were adjusted according to the participant’s response in the previous trial. This procedure was repeated until participants pressed ‘Q’, indicating that the sphere’s motion looked to be natural.

2.5 Experimental design

Participants were presented with three scenarios: the *acceleration adjustment-frictionless* (*A-NoF*) scenario, the *acceleration adjustment-friction* (*A-F*) scenario, and the *density adjustment* (*D*) scenario. The presentation order of the scenarios was counterbalanced across participants. Participants were not informed about the existence of three different scenarios and were only asked to adjust the falling speed of the sphere until the vertical fall was perceived as natural. The *A-NoF* scenario simulated the vertical fall of the spheres in a vacuum, according to Equation 1, whereas the *A-F* scenario simulated the vertical fall of the spheres on Earth, according to Equation 2. In the *A-F* scenario, parameter m was set to .055 kg for the wooden sphere and to .005 kg for the polystyrene sphere, and for both spheres C_d = .47, ρ = 1.2047 kg/m^3 and A = .0019625

m^2. These were the physical parameters for the real wooden and polystyrene spheres that were presented to the participants at the beginning of the experiment. In both acceleration adjustment scenarios, the to-be-adjusted parameter was a, that is, the simulated gravitational acceleration (see Equations 1 and 2). The *D* scenario still followed Equation 2 but, unlike previous scenarios, participants actually adjusted the simulated density of the medium in which the vertical fall took place (i.e., parameter ρ), while the simulated gravitational acceleration was kept constant at its physically correct value ($a = g \approx 9.81$ m/s^2).

In each trial of each scenario, the physically correct value of the to-be-adjusted parameter (i.e., 9.81 m/s^2 in the *A-NoF* and the *A-F* scenarios, 1.2047 kg/m^3 in the *D* scenario) was multiplied by a variable k, according to the following design. Each scenario was divided into four ‘staircases’ of variable duration obtained from the factorial combination of two levels of simulated material (i.e., wood or polystyrene) and two possible directions of the staircase (i.e., ascending or descending). Within each scenario, the four staircases were presented in random order. The ascending and descending staircases differed in the starting value of k, which was .1 for ascending staircases and 2.5 for descending staircases. In other words, the starting value of the ascending (descending) staircases was $a = g \times .1$ ($a = g \times 2.5$) in the *A-NoF* and the *A-F* scenarios, and $\rho = 1.2047$ kg/m$^3 \times .1$ ($\rho = 1.2047$ kg/m$^3 \times 2.5$) in the *D* scenario. In the two acceleration adjustment scenarios, after a ‘Z’ (‘M’) response in trial n of the staircase, indicating that in that trial the falling speed appeared too fast (too slow), in trial $n + 1$ the value of k was decreased (increased) by .05. On the contrary, because vertical falling speed decreases with the simulated density of the medium, in the density adjustment scenario the value of k was increased by .05 after a ‘Z’ response and decreased by the same value after a ‘M’ response. Each staircase was terminated when the participant pressed ‘Q’, indicating that the simulated vertical fall appeared to be natural.

The last value of k in an ascending staircase, multiplied by the physically correct value of the to-be-adjusted parameter (i.e., g in the *A-NoF* and *A-F* scenarios, 1.2047 kg/m^3 in the *D* scenario), determined the *lower naturalness bound*, that is, the smallest value of the parameter giving rise to a perceptually natural fall. Symmetrically, the last value of k in a descending staircase, multiplied by the physically correct value of the to-be-adjusted parameter, determined the *upper naturalness bound*, that is, the largest value of the parameter giving rise to a perceptually natural fall. The interval of values between the upper and lower naturalness bounds determines the *naturalness interval*, which can be defined as the range of values of the to-be-adjusted parameter corresponding to perceptually natural falls. Two properties of the naturalness interval are particularly relevant for our study: *position* and *width*. The position corresponds to the mean between the upper and lower naturalness bounds (midpoint). Compared with the physically correct value of the corresponding parameter, the position of the naturalness interval provides an index of participants' accuracy. If the strength of the naturalness impression is assumed to be normally distributed within the naturalness interval, then the position of the naturalness interval can be interpreted as the value of the physical parameter that is perceived as the most 'natural' by the participants. The width of the naturalness interval corresponds instead to the difference between the upper and lower naturalness bounds, and can be conceived as an indirect measure of participants' uncertainty about the 'natural' parameters. A wide naturalness interval indicates that a broad range of values of the physical parameter give rise to perceptually natural falls. A high level of accuracy in the position of the naturalness interval, combined with a relatively small width of the interval, would provide support to the hypothesis of a good intuitive knowledge of the physics of gravitational motion.

2.6 Experimental hypotheses

Experiment 1 mainly aimed at contrasting two different hypotheses, namely that perceptual judgments of the naturalness of vertical falls rely on an internalized representation of Equation 2, and that they rely on a weight-based heuristic. We first discuss the predictions from the internalization hypothesis, and then the predictions from the heuristic hypothesis.

In a vacuum (i.e., in the *A-NoF* scenario), for a fixed value of simulated gravitational acceleration a, the wooden and the polystyrene sphere would fall exactly with the same acceleration (see the two leftmost columns in Figure 1). However, consistently with the hypothesis of an internalized representation of Equation 2, participants might expect that the polystyrene sphere should fall slightly slower with respect to the wooden sphere (see the two rightmost columns in Figure 1). If this was the case, then in the *A-NoF* scenario the position of the naturalness interval for the simulated polystyrene should be smaller than that for the simulated wooden sphere. Specifically, in the current context, when the effects of air resistance are accounted for (i.e., as in the *A-F* and the *D* scenarios), an acceleration g for the wooden and the polystyrene spheres implies that the ‘average speed’ of the wooden sphere (in deg/s) is 7.6% larger than the one of the polystyrene sphere[1]. In other words, the wooden sphere falls slightly faster than the polystyrene sphere. Therefore, if participants had a correct internalized representation of Equation 2, then they would expect some difference between the speeds of the wooden and the polystyrene sphere also in the *A-NoF* scenario, in spite of the fact that, in such a scenario, the falling motions are actually identical. Specifically, if g is the acceleration of the wooden sphere, then, in order to obtain a 7.6% difference in average speeds in the *A-NoF* scenario, the polystyrene sphere should fall with an acceleration 9.17 m/s^2. By contrast, in the realistic *A-F* scenario where the simulated spheres moved coherently with Equation 2, the positions of the naturalness intervals should instead be identical to each other and consistent with the physically correct value g. The simulated spheres moved according to Equation 2 also in the *D* scenario, therefore the positions of the naturalness intervals for the simulated polystyrene and wooden spheres are expected to be identical to each other and consistent with the physically correct value 1.2047 kg/m^3. As for the width of the naturalness intervals, if the hypothesis that participants rely on internalized knowledge of Equation 2 is correct, then in all scenarios participants should exhibit low levels of uncertainty about the ‘natural’ parameters, therefore the widths of the naturalness intervals should be relatively small. However, the widths of the naturalness intervals might not only depend on uncertainty about the ‘natural’ parameters but also on the sensitivity of the visual system to differences between the motion patterns of the simulated falls. For instance, independently of the simulated material, if participants were not able to discriminate a simulated fall with acceleration g from other simulated falls with respectively accelerations 8.5 and 11 m/s^2, then all the accelerations in the interval between 11 m/s^2 and 8.5 m/s^2 would look ‘natural’. In other words, in this case a width of 11 m/s^2 - 8.5 m/s^2 = 2.5 m/s^2 would be attributed exclusively to the limited sensitivity of the visual system to differences between the accelerations of the simulated falls, rather than to the uncertainty about the ‘natural’ parameters. Based on the results of a previous study by Werkhoven et al. (1992), we tentatively assume that a difference between two simulated falls can be perceived when there is at least a 6% difference between the corresponding average speeds (in deg/s)[2]. We use this threshold value to test if the simulated

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[1] The average speed is given by $v_{average} = (v_{final} - v_{initial})/2$, where v_{final} is the speed of the simulated sphere when the lower edge of the sphere ‘touches’ the lower limit of the screen and $v_{initial}$ is always equal to 0 deg/s because the simulated spheres always started from stationary.

[2] Previous studies on the sensitivity of observers to an accelerated motion have focused on the perceptual comparison between pairs of targets characterized by the same average speed, one target moving at uniform acceleration and the

falls corresponding to the upper and lower naturalness bounds could be discriminated from those corresponding to the midpoints of the naturalness intervals. Failing such condition would lend support to the hypothesis that the widths of the naturalness intervals depended only on the lack of sensitivity to differences between the motion patterns of the simulated falls, which in turn would provide support for the internalization hypothesis. Moreover, we will use this 6% threshold value to test if the simulated falls corresponding to the midpoints of the naturalness intervals could be discriminated from those associated to the physically correct values of the parameters. Indeed, a discrepancy between the midpoint of the naturalness interval and the physically correct value of the parameter may not be a definitive proof against the internalization hypothesis, unless participants could see the difference between these simulated falls.

A possible alternative to the hypothesis that participants possess an internalized representation of Equation 2 is that they rely on a weight-based heuristic representation of gravitational motion that is unrelated (or loosely related) to Equation 2. Based on such heuristic, participants might expect the difference in the average falling speed of the polystyrene and of the wooden sphere to be larger than predicted by Equation 2. If this hypothesis is correct, then a difference between the position of the naturalness intervals for the wooden and the polystyrene sphere should emerge in all scenarios, irrespectively of the simulated effects of air resistance. Specifically, the position of the naturalness interval for the wooden sphere should be higher than that for the polystyrene sphere in both the *A-NoF* and the *A-F* scenario, whereas the opposite should be true in the *D* scenario. In the latter scenario, indeed, the average speed of the sphere decreases as the parameter ρ increases, therefore if one expects the polystyrene sphere to fall slower than the wooden sphere, then the corresponding adjusted value of ρ should be higher for the polystyrene sphere. All these hypothetical differences should be clearly perceivable. Moreover, consistently with the hypothesis of a heuristic representation of gravitational motion, it can be predicted that participants would exhibit relatively

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other target moving at constant velocity (e.g., Calderone & Kaiser, 1989; Gottsdanker et al., 1961; Mueller & Timney, 2016; Schmerler, 1976; Werkhoven et al., 1992). However, in contrast to these studies, in Experiment 1 the accelerations of the simulated spheres co-vary with their average speeds (see also Note 1). In such a case, the focus is not on quantifying the participants' ability to discriminate uniform acceleration from uniform speed in presence of motion stimuli characterized by the same average speed, but rather in quantifying the participants' ability to discriminate accelerated motions characterized by different average speeds. Relatively to this point, in a speed discrimination task, Werkhoven et al. (1992) found that the speeds of two targets could be discriminated (accuracy = .80) when there was a 6% difference between their physical speeds (in deg/s). Based on this result, we can tentatively assume that a difference between two simulated falls could be perceived when there is at least a 6% difference between the average speeds of the spheres (in deg/s). It is however important to stress that the 6% discrimination threshold found by Werkhoven et al. (1992) refers to stimuli moving at a constant velocity, therefore the use of this discrimination threshold in the context of accelerated stimuli should be taken with a certain caution.

high level of uncertainty about the ‘natural’ parameters. If this hypothesis is correct, then the difference between the simulated falls corresponding to the midpoints of the naturalness intervals and those corresponding to the upper and lower naturalness bounds should be clearly perceivable. This would indicate that the widths of the naturalness intervals do not reflect only a lack of observers’ sensitivity to the differences between the motion patterns of the simulated falls, but also their uncertainty about the ‘natural’ parameters.

2.8 Results and discussion

The position and width of the naturalness intervals are the dependent variables of this first experiment. It should be noted that, in both acceleration adjustment scenarios (i.e., *A-NoF* and *A-F*), position and width refer to the physical parameter a, therefore they can be compared with each other across scenarios. Conversely, the position and the width in the *D* scenario refer to the parameter ρ, therefore they cannot be directly compared with those obtained in the acceleration adjustment scenarios.

The mean upper and lower naturalness bounds for the three scenarios and for each of the two simulated materials are reported in Table 1, together with the 95% confidence intervals. They were obtained by averaging the upper and lower naturalness bounds across the 30 participants. Figure 3 shows the boxplots and the violin plots for the position (panels a-c, top row) and the width (panels d-f, bottom row) of the naturalness intervals for each simulated material. Black thin lines were added to show the trend of individual data. The red dotted line in the three top panels indicates the correct value of the to-be-adjusted physical parameter (i.e., 9.81 m/s^2 for a, 1.2047 kg/m^3 for ρ).

Scenario	**Material**	**Lower Naturalness Bound**	**Upper Naturalness Bound**
A-NoF	Poly	3.662 m/s^2 95% CI [2.94, 4.38]	7.717 m/s^2 95% CI [6.03, 9.40]
A-NoF	Wood	5.69 m/s^2 95% CI [4.95, 6.43]	11.56 m/s^2 95% CI [10.28, 12.87]
A-F	Poly	3.953 m/s^2 95% CI [3.19, 4.71]	7.828 m/s^2 95% CI [6.38, 9.27]
A-F	Wood	6.281 m/s^2 95% CI [5.43, 7.13]	11.674 m/s^2 95% CI [10.46, 12.89]
D	Poly	1.253 kg/m^3 95% CI [1.64, 1.34]	1.795 kg/m^3 95% CI [1.67, 1.91]

D	Wood	.953 kg/m^3 95% CI [.85, 1.05]	1.36 kg/m^3 95% CI [1.24, 1.48]

Table 1. Average lower and upper naturalness bounds from Experiment 1 with 95% confidence intervals, for each scenario and each simulated material.

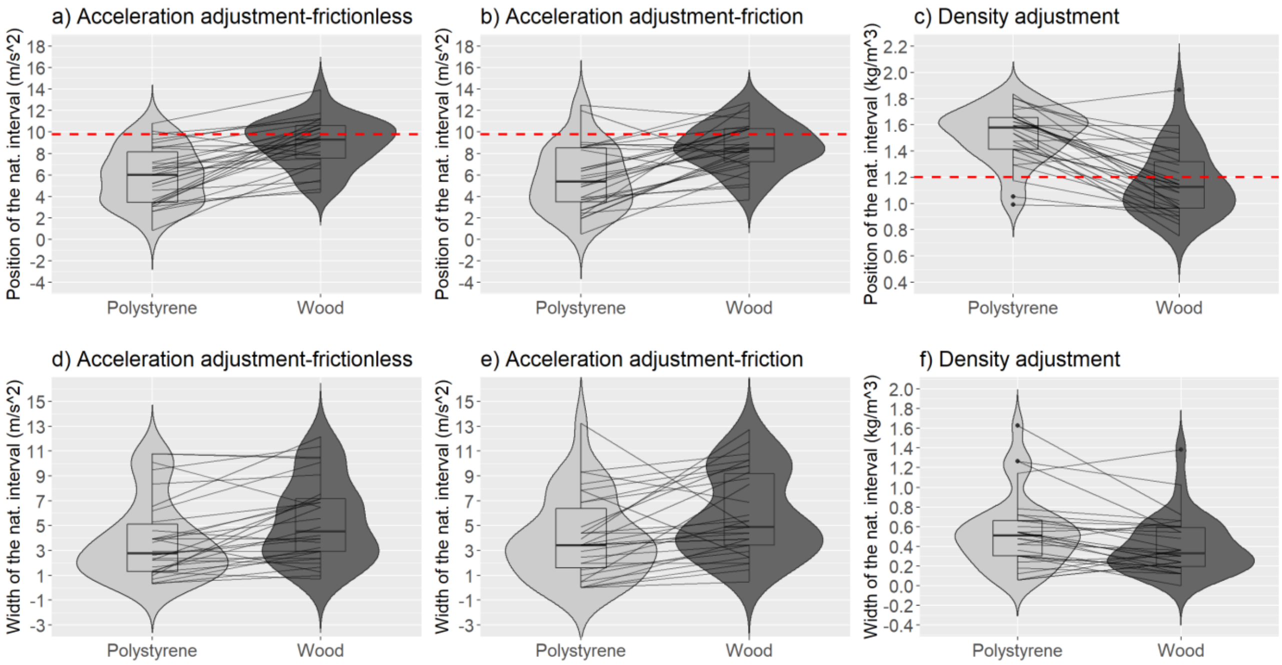

Figure 3. Boxplots and violin plots for the position (top row) and the width (bottom row) of the naturalness intervals in Experiment 1, for each scenario (different columns) and each simulated material (horizontal axis and different shades). The dashed red line in the top panels indicates the physically correct value of the corresponding to-be-adjusted parameter (i.e., $a = g$ in panels a and b, $\rho = 1.2047$ kg/m^3 in panel c).

We first focus on the analysis of the position of the naturalness intervals, and then on the analysis of the width of the naturalness intervals. Shapiro-Wilk normality tests showed that the distribution of the position of the naturalness intervals was not significantly different from normal in any of the six conditions 3 (Scenario) ✕ 2 (Material) (*Ws* > .94, *ps* > .08).

We first compared the position of the naturalness intervals in the two acceleration adjustment scenarios. The results of an ANOVA 2 (Scenario) ✕ 2 (Material) showed that the only statistically significant effect was Material ($F(1,29) = 38.67$, $p < .001$, $\eta_G^2 = .26$). The absence of a statistically significant main effect of Scenario ($F(1.29) = 1.23$, $p > .10$, $\eta_G^2 = .003$) and of the two-way interaction ($F(1.29) = .16$, $p > .10$, $\eta_G^2 = .0002$) suggests that the positions of the naturalness intervals did not differ across the two scenarios. Results of two paired-sample two-tailed *t*-tests supported the hypothesis that, in both acceleration adjustment scenarios, the mean position of the naturalness intervals for the wooden sphere was larger than the mean position of the naturalness intervals for the polystyrene sphere. In the *A-NoF* scenario we obtained $M = 5.89$ m/s^2, 95% CI [4.91, 6.88] for the polystyrene sphere and $M = 8.98$ m/s^2, 95% CI [8.14, 9.82] for the wooden sphere ($t(29) = -6.77$, $p < .001$, $d_z = -1.24$). In the *A-F* scenario we obtained $M = 5.69$ m/s^2, 95% CI [4.56, 6.82] for the polystyrene sphere and $M = 8.63$ m/s^2, 95% CI [7.8, 9.47] for the wooden sphere, ($t(29) = -5.16$, $p < .001$, $d_z = -.94$). By contrast, in the *D* scenario the mean position of the naturalness intervals for the wooden sphere ($M = 1.16$ kg/m^3, 95% CI [1.06, 1.25]) was significantly smaller than the mean position of the naturalness intervals for the polystyrene sphere ($M = 1.52$ kg/m^3, 95% CI [1.45, 1.60]), $t(29) = -7.78$, $p < .001$, $d_z = -1.42$). In order to quantify the magnitude of the effects of the simulated material on the relative positions of the naturalness intervals in the three scenarios, for each participant we calculated the difference between the position of the naturalness interval for the wooden sphere and the position of the naturalness interval for the polystyrene sphere (Δ_{pos}). The mean value of Δ_{pos} was 3.09 m/s^2, 95% CI [2.15, 4.01] in the *A-NoF* scenario, 2.94 m/s^2, 95% CI [1.78, 4.11] in the *A-F* scenario, and -.367 kg/m^3, 95% CI [-.464, -.271] in the *D* scenario. A Bayesian *t*-test showed that the null hypothesis of the absence of difference between Δ_{pos} in the two acceleration adjustment scenarios was almost five times more likely than the alternative hypothesis of the presence of a difference ($BF_{01} = 4.77 \pm .01\%$). A positive Δ_{pos}, indicating that the position of the naturalness interval for wood was higher than that for polystyrene, emerged for 27 out of 30 participants in the *A-NoF* scenario, for 25 participants in the *A-F* scenario, and for only 3 participants in the *D* scenario. Overall, these results reveal a strong effect of simulated material on the position of the naturalness intervals in all three scenarios, which provides clear evidence against the hypothesis that the naturalness judgments were based on a faithful internalized representation of Equation 2. To be perceived as natural, the acceleration of the polystyrene sphere had to be clearly smaller than the acceleration of the wooden sphere.

We also tested the consistency of the effects of simulated material on the positions of the individual naturalness intervals across the three scenarios, by computing correlations between the individual Δ_{pos} for each pair of scenarios. The correlations between the individual Δ_{pos} were $r = .78$, 95% CI [.59, .89], $p <.001$ for the *A-NoF*/*A-F* pair, $r = -.72$, 95% CI [-.86, -.48], $p < .001$, for the the *A-NoF*/*D* pair, and $r = -.68$, 95%

CI [-.84, -.42], $p < .001$ for the *A-F*/*D* pair. These results suggest that, at the individual level, the effects of simulated material on the perceived naturalness of the simulated vertical falls were consistent across the scenarios. This finding provides some support to the hypothesis that participants' responses in the three scenarios were driven by a common weight-based heuristic process, according to which a relatively light sphere should fall more slowly than a relatively heavier one.

As for the absolute accuracy of the positions of the naturalness intervals, single-sample two-tailed *t*-tests showed that, in the *A-NoF* scenario, the mean position of the naturalness intervals for the simulated polystyrene sphere was significantly smaller than 9.81 m/s^2 ($t(29) = -8.13$, $p < .001$, $d_z = -1.48$). Conversely, the mean position of the naturalness intervals for the simulated wooden sphere was not significantly different from 9.81 m/s^2 ($t(29) = -2.02$, $p = .052$, $d_z = -.37$). In the *A-F* scenario, instead, the mean position of the naturalness intervals was significantly smaller than 9.81 m/s^2 both for the simulated polystyrene sphere ($t(29) = -7.43$, $p < .001$, $d_z = -1.36$) and for the simulated wooden sphere ($t(29) = -2.87$, $p < .01$, $d_z = -.52$). Notice that in this latter scenario, the underestimation is more pronounced for the polystyrene sphere than for the wooden sphere. As to the *D* scenario, the mean position of the naturalness intervals for the simulated polystyrene sphere was significantly larger than 1.2047 kg/m^3 (i.e., air's density at 20 °C) ($t(29) = 8.31$, $p < .001$, $d_z = 1.52$). Conversely, the mean position of the naturalness intervals for the simulated wooden sphere was not significantly different from the physically correct value ($t(29) = -1.02$, $p > .10$, $d_z = -.19$). Overall, these results indicate a substantially unbiased representation of the vertical fall of the wooden sphere, whereas the falling speed of the polystyrene sphere was clearly underestimated in all scenarios. For the polystyrene sphere, the physically correct value of gravitational acceleration g was not even included in the mean naturalness intervals of the two acceleration adjustment scenarios (see Table 1), meaning that the physically correct gravitational acceleration was perceived as unnatural (i.e., too fast) by most observers. Participants tended instead to perceive as natural acceleration values less than one-half the value of g. In the *D* scenario, the motion of the polystyrene sphere appeared to be natural when the fall took place in a medium with simulated density larger than 1.2047 kg/m^3 (i.e., air density at 20 °C). Once again, the physically correct value of density was not even included in the mean naturalness interval (see Table 1).

As regards the widths of the naturalness intervals, Shapiro-Wilk normality tests showed that, in the two acceleration adjustment scenarios, the distributions of the widths for the polystyrene sphere significantly differed from normal (W =.87, $p < .005$ in the *A-NoF* scenario, W =.92, $p < .05$ in the *A-F* scenario). We thus applied a square-root transformation, which normalized the distributions (*W*s > .94, *p*s > .10). A two-way ANOVA 2 (Scenario) ✕ 2 (Material) on the transformed data showed that the only statistically significant factor was Material ($F(1,29) = 22.55$, $p < .001$, $\eta_G^2 = .08$). As it can be seen in Figure 3, the naturalness intervals for the wooden sphere tended to be wider than those for the polystyrene sphere. The main effects of factor Scenario ($F(1,29) = .08$, $p > .10$, $\eta_G^2 \approx 0$) and of the two-way interaction were not statistically significant ($F(1,29) = .87$, $p > .10$, $\eta_G^2 = .002$). This result suggests that there were no differences between the more realistic and the less realistic acceleration adjustment scenario regarding the uncertainty around the acceleration values perceived to be natural by the observers[3]. A Bayesian *t*-test showed that the null hypothesis of no difference between the transformed widths of the naturalness intervals of the two scenarios was about five times more likely than the alternative hypothesis of a difference between them ($BF_{01} = 5.14 \pm 0.02\%$). Regarding the widths of the naturalness intervals in the *D* scenario, Shapiro-Wilk tests showed that the distribution differed from normal in a statistically significant manner, both for polystyrene ($W = .896$, $p < .01$), and for wood ($W = .874$, $p < .005$). Because we could not normalize by means of a simple transformation, we used a Wilcoxon test which showed that the mean width of the naturalness intervals for the wooden sphere was larger than that for the polystyrene sphere ($V = 110$, $p < .05$).

It is also important to determine the extent to which the widths of the naturalness intervals may reflect the participants' uncertainty about the 'natural' parameters, or only a lack of visual sensitivity to differences between the motion patterns of the simulated falls. In this regard, the third (fourth) column of Table 2 shows, for each scenario and each simulated material, the percentage difference between the average speed of the simulated fall corresponding to the mean lower (upper) naturalness bound and the average speed of the simulated fall corresponding to the midpoint of the mean naturalness interval. Recall that we tentatively assumed that differences between the simulated falls could be perceived when the percentage differences between the average speeds were in absolute value equal to or larger than 6% (see Note 2). In both the *A-NoF* and the *A-F* scenario, the percentage differences were clearly larger than this threshold value for both simulated materials, confirming that the widths of the naturalness intervals largely reflected the

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[3] An ANOVA on the untransformed data confirmed the results of the ANOVA on the transformed data. The main effect of factor Material was statistically significant ($F(1,29)= 19.02$, $p < .005$, $\eta_G^2 = 0.061$), whereas the main effects of factor Scenario and of the interaction were not statistically significant ($F(1,29) = 0.42$, $p > .10$, $\eta_G^2 = 0.002$, and $F(1,29) = 0.17$, $p > .10$, $\eta_G^2 \approx 0$).

participants' uncertainty about the 'natural' parameters. By contrast, in the *D* scenario, the absolute percentage differences were clearly smaller than 6%, suggesting that in this scenario the participants could not perceive the difference between the simulated falls corresponding to the midpoint of the mean naturalness interval and the simulated falls corresponding to the mean naturalness bounds. As it will be discussed in more details below, this latter result is probably due to the small range of variation of the motions of the simulated spheres in this scenario. The fifth column in Table 2 also shows the percentage difference between the average speed corresponding to the midpoint of the mean naturalness interval and the average speed corresponding to the physically correct value of the physical parameter (i.e., g or $\rho = 1.2047$ kg/m^3). For the polystyrene sphere, a large percentage difference emerged both in the *A-NoF* and in the *A-F* scenario, suggesting that the strong discrepancy between the midpoint of the mean naturalness interval and the physically correct parameter could not be exclusively due to the lack of participants' sensitivity to differences between the corresponding simulated falls.

Scenario	**Material**	**Midpoint vs. Lower Bound**	**Midpoint vs. Upper Bound**	**Midpoint vs. Physically correct**
A-NoF	Poly	23.4%	- 15.3%	- 28.7%
A-NoF	Wood	21.3%	- 12.4%	- 6.1%
A-F	Poly	21.0%	- 14.4%	- 26.9%
A-F	Wood	18.0%	- 12.0%	- 4.2%
D	Poly	- 1.6%	1.5%	- 1.8%
D	Wood	- .1%	.1%	0.0%

Table 2. For each scenario and each simulated material, this table shows the percentage differences between the average speed (in deg/s) for the midpoint of the mean naturalness interval and: 1) the average speed for the mean lower naturalness bound (third column), 2) the average speed for the mean upper naturalness bound (third column), 3) the average speed for the corresponding physically correct value. It is assumed that a difference between two simulated falls can be perceived when the absolute value of the percentage difference between their average speeds is equal or larger than 6%.

An alternative representation of the results of Experiment 1 (Figure 3) is provided by the position-velocity graphs in Figure 4. These graphs represent the velocity of the simulated sphere as a function of its position (horizontal axis) for different possible values of the to-be-adjusted parameter (separate curves), for each scenario and each of the two simulated materials. Each curve shows, for a specific value of the to-be-adjusted parameter, how the velocity of the simulated sphere varies as a function of its position, provided that 2.162 m is the initial distance of the simulated sphere from the terminal point and 0 m is the terminal point of the descent. Specifically, in each graph the dashed red curve represents the position-velocity pattern corresponding to the physically correct value of the to-be-adjusted parameter, the thick black curve represents the position-velocity pattern corresponding to the mean position of the naturalness intervals, and the dash-dotted blue curves represent the position-velocity patterns for the mean upper and lower naturalness bounds. The thin gray lines represent the motion patterns corresponding to the position of the naturalness interval for each of the 30 participants. Unlike the graphs in Figure 3, the graphs in Figure 4 allow a direct comparison between the results of the two acceleration adjustment scenarios (panels a-d) and the results of the density adjustment scenario (panels e and f). In panels a and c, the lower position of the thick black curve and the dash-dotted blue curves with respect to the dashed red curve reflects the underestimation of the gravitational acceleration for the simulated polystyrene sphere; in panel e, it reflects the overestimation of medium density for the simulated polystyrene sphere.

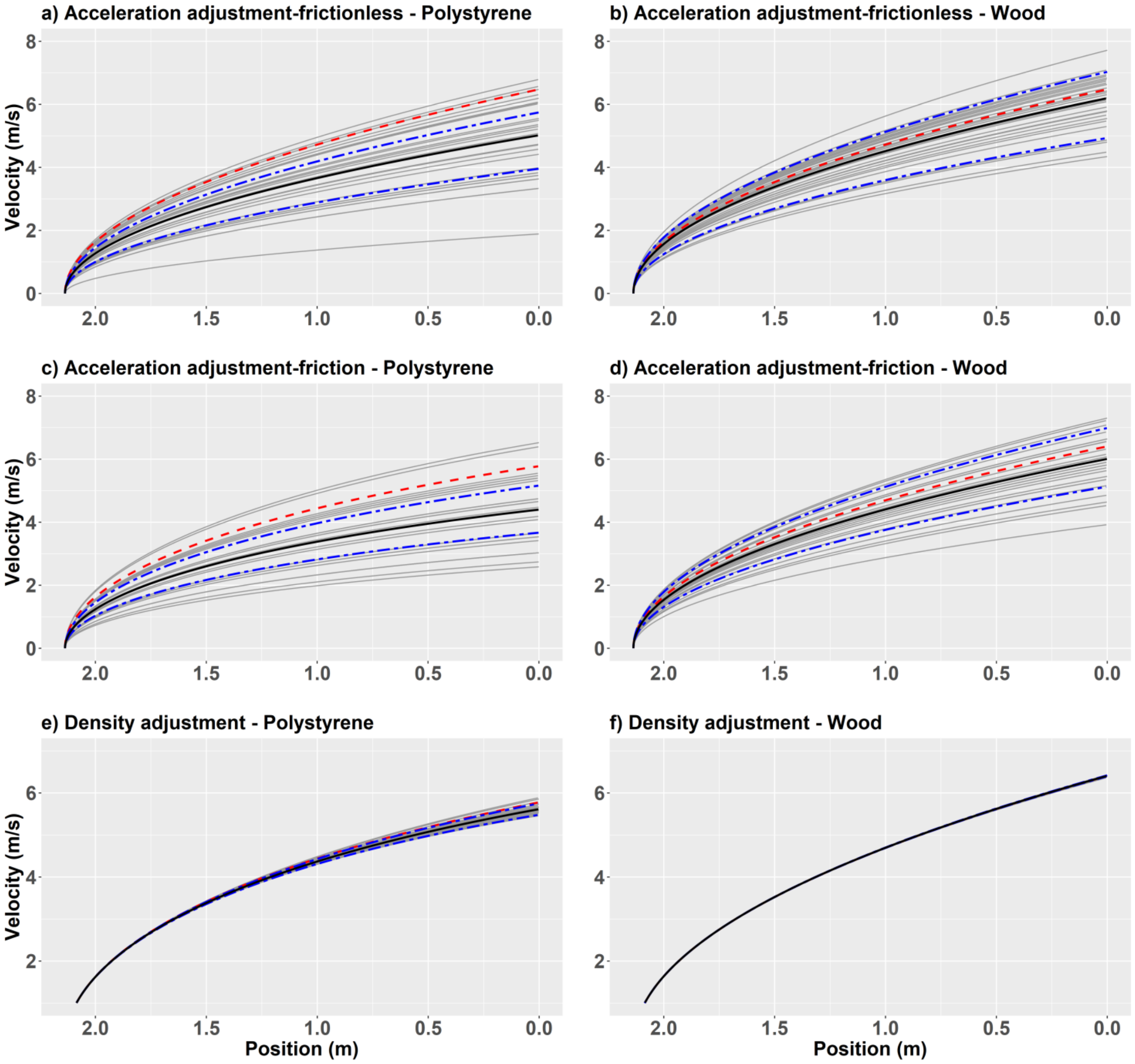

Figure 4. Data from Experiment 1. Note that 2.162 m is the initial distance of the simulated sphere from the terminal point and 0 m is the terminal point of the descent. Each panel represents the position-velocity pattern of the sphere (polystyrene in the left panels, wood in the right panels) corresponding to the mean position of the naturalness interval (thick black curve), to the mean estimated upper and lower naturalness bounds (blue dash-dotted curves), to the physically correct value of the to-be-adjusted parameter (red dashed curve), and to the positions of the individual naturalness intervals of the 30 participants (gray lines).

Figure 4 shows a marked contrast between the variation in the patterns in panels a-d, and the variation in the patterns in panels e-f corresponding to the *D* scenario. It is important to stress that the strikingly apparent accuracy in the latter case should not be taken at face value as evidence of an increased sensitivity of the participants to density manipulation. Rather, it is a consequence of the model itself and of how the parameters g and ρ enter Equation 2. Consider the graphs in Figure 5, representing the position-velocity pattern for six possible values of the variable *k* in the interval .1-2.5 (ascending-descending staircases). The range of variation of *k* in the interval .1-2.5 does not allow in the case of density manipulation (panels e-f) for a variation of patterns on the same scale as for the case of acceleration manipulation (panels a-d). Specifically, the manipulation of simulated density has a very small effect on the motion pattern of the simulated wooden sphere, and only a slightly bigger effect on the motion pattern of the simulated polystyrene sphere. Nonetheless, it is remarkable that in spite of such reduced variation, participants still overestimated the simulated density of the medium in the *D* scenario of Experiment 1 for the polystyrene sphere (see the penultimate row in Table 1).

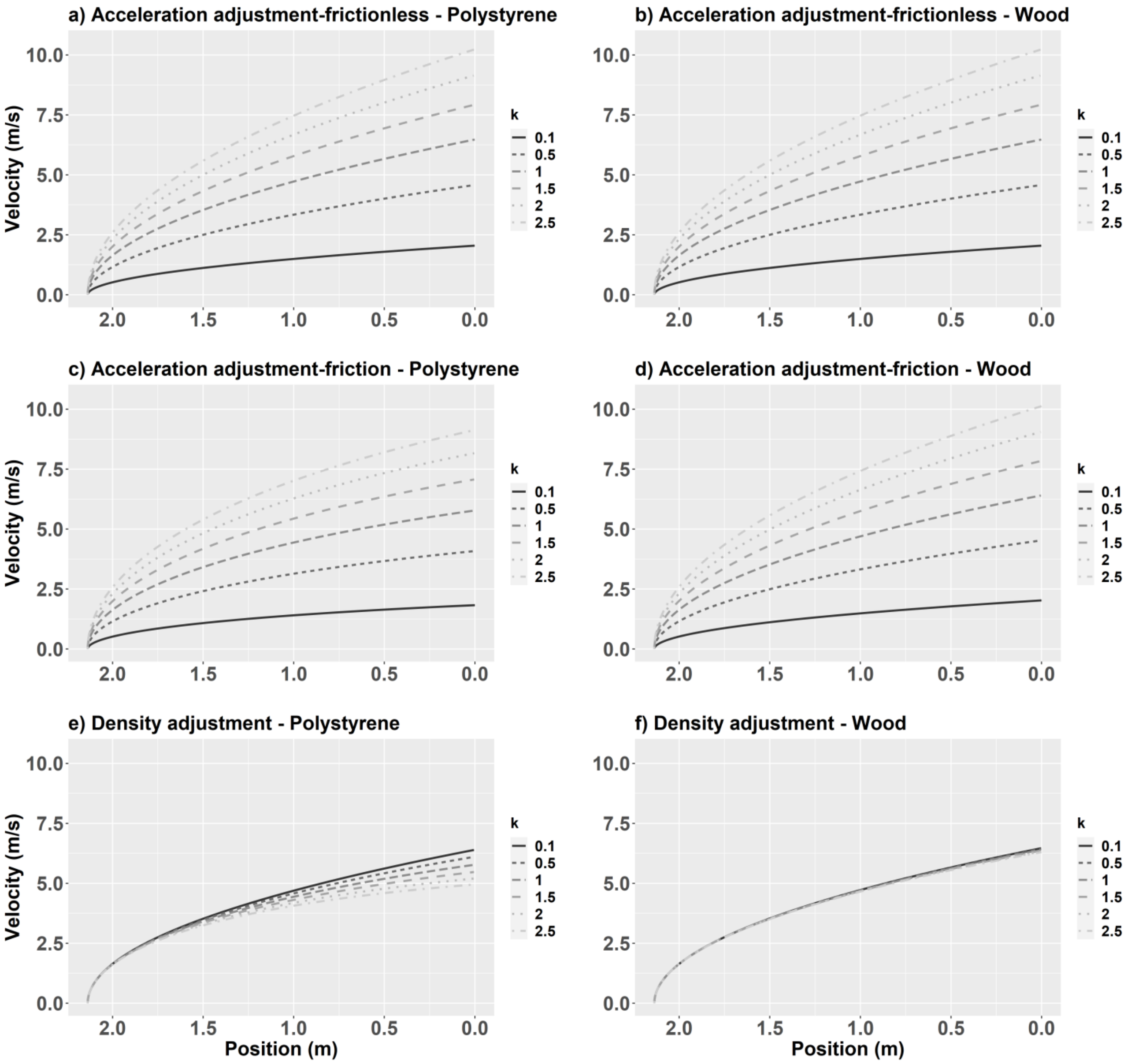

Figure 5. Each panel represents the velocity of the sphere (polystyrene in the left panels, wood in the right panels) as a function of its position and of the variable *k*, computed from Equation 1 (panels a and b) and from Equation 2 (panels c-f). The spread of the curves provides an idea of the effects of the manipulation of *k* on the motion pattern of the sphere.

2.9 Explorative analysis: effects of formal instruction in physics

In line with previous intuitive physics studies (e.g., Cooke & Breedin, 1994; McCloskey et al., 1980; McCloskey & Kohl, 1983), we also tested if participants' responses were affected by their level of education in physics. Specifically, we explored whether effects of simulated material on the relative positions of the naturalness intervals were smaller for participants with relatively high levels of physics education than for participants with relatively low levels. An important premise of this analysis is that it can only provide tentative results, since the sample was not chosen to enable an exhaustive test of this specific hypothesis. For this reason, only qualitative (i.e., graphical) analyses of the results are provided.

Figure 6 shows, separately for each scenario, the Δ_{pos} (top panels) and the widths of the naturalness interval averaged across the two simulated materials (bottom panels) as a function of the number of years of formal training in physics. Results show the absence of a clear trend, which provides tentative support to the hypothesis that formal training in physics did not affect the participants' performance in Experiment 1.

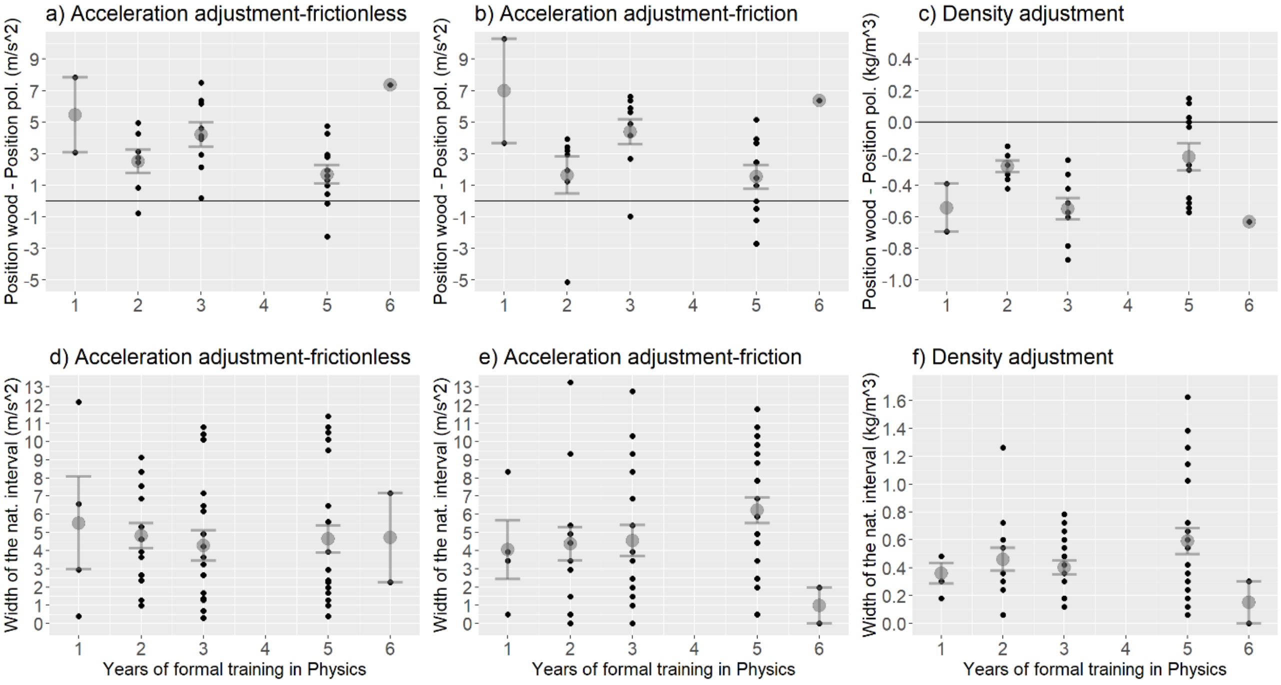

Figure 6. The black dots indicate the individual Δ_{pos} (top panels) and the individual width of the naturalness intervals from Experiment 1, averaged across the two simulated materials (bottom panels) as a function of the participant's number of years of formal training in physics, separately for each scenario. The large grey dots correspond to the mean of Δ_{pos} and width for each group of participants, the error bars represent the standard error of the mean.

3. Experiment 2

Results from Experiment 1 suggest that both positions and widths of the naturalness intervals were independent of the realism of the scenario, that is, they were independent of the presence or absence of the simulated effects of air drag. However, in Experiment 1 participants did not directly compare with each other stimuli from different scenarios. This leaves open the possibility that stimuli from the realistic *A-F* and *D* scenarios could still be perceived as more natural compared with stimuli from the unrealistic *A-NoF* scenario. Experiment 2 aimed at providing a direct test of the influence of the realism of the scenario on the perceived naturalness of simulated vertical falls.

In Experiment 1, each participant estimated six naturalness bounds (3 scenarios × 2 staircase directions) for each simulated material (i.e., wood and polystyrene). Using a 2-AFC paradigm, in Experiment 2 the same participants of Experiment 1 were asked to directly compare the perceived naturalness of the stimuli corresponding to the six naturalness bounds that they had previously estimated. The two simulated materials were presented in separate blocks, that is, in each block the participant compared the perceived naturalness of the six naturalness bounds for a specific simulated material. Materials were never mixed. In each trial, one of the 6 × 6 = 36 possible ordered pairs of naturalness bounds stimuli was presented, and participants were asked to indicate which of the two stimuli appeared to be more natural. If participants have a definite preference for realistic stimuli characterized by the presence of the simulated effects of air resistance, then the stimuli from the *A-F* scenario and the stimuli from the *D* scenario should be judged as 'more natural' with greater probability than the stimuli from the *A-NoF* scenario. Furthermore, recall that in Experiment 1 the motion patterns corresponding to the mean upper and lower naturalness bounds in the *D* scenario were remarkably similar to the physically correct motion pattern (see the fifth column of Table 2 and panels e-f in Figure 4). If participants have a definite preference for stimuli that are consistent with

Equation 2, then they should exhibit a clear tendency to perceive the stimuli from the *D* scenario as more natural than the stimuli from the other scenarios.

3.1 Participants

Participants were the same as in Experiment 1. Experiment 2 took place at least two days after Experiment 1. Together with the fact that the experimental task was quite different from that of Experiment 1, this should minimize possible carry-over effects.

3.2 Apparatus

The apparatus was the same as in Experiment 1 (see Figure 2).

3.3 Stimuli and Procedure

The stimuli were the same as in Experiment 1. Before starting the experimental session, the two real wooden and polystyrene spheres were presented once again to the participants, who could manipulate them for about 30 s, as in Experiment 1.

Participants were then provided with written instructions describing the experimental procedure. In each trial two simulated vertical falls were presented one after the other, separated by a 500 ms blank screen. After the presentation of the second simulated fall, participants were asked to indicate which of the two falls appeared to be more natural (i.e., more consistent with the fall from that height of the real wooden or polystyrene sphere). Participants had to press ‘Z’ if the first fall was perceived as more natural or ‘M’ for the second. A new trial was then presented 1 s after their response.

3.4 Experimental design

Since the participants might find it difficult to compare the naturalness of the falling motion of stimuli made of different simulated materials, wooden and polystyrene spheres were presented in different blocks in counterbalanced order.

Experiment 2 focused on the possible influence of the realism of the scenario on the perceived naturalness of virtually simulated falls. A possible experimental design could be to sample a fixed set of values of the physical parameters from the three scenarios in Experiment 1, and make participants compare the perceived naturalness of stimuli corresponding to these values of the parameters. However, a drawback of such an approach would be that the participant's response would depend both on the realism of the scenario and on the individual naturalness intervals for each scenario. For instance, for a given participant, a fixed value of simulated gravitational acceleration might correspond to both a stimulus lying within the naturalness interval for the *A-F* scenario and to a stimulus lying outside of the naturalness interval for the *A-NoF* scenario. If two such stimuli were directly compared with each other, the *A-F* stimulus might be judged as more natural than the *A-NoF* stimulus, yet it would be still unclear whether the result depends on a higher level of realism of the *A-F* stimulus or on the fact that only the former stimulus was perceived as natural within its scenario. In order to minimize this possible confound, the stimuli that were compared with each other in Experiment 2 needed comparable levels of perceived naturalness within their scenario; for instance, the *A-F* stimulus and the *A-NoF* stimulus needed to both fall within the naturalness interval in the respective scenarios.

In line with these considerations, in each of the two blocks of Experiment 2 participants compared with each other the six stimuli (for each material) corresponding to the upper and the lower naturalness bounds of Experiment 1 (3 scenarios × 2 bound types). Two repetitions of the 36 possible ordered pairs of the stimuli were presented, for a total of 144 stimulus pairs for each participant (i.e., 72 pairs for each block) In all scenarios, the upper (lower) naturalness bound was the largest (smallest) value of the to-be-adjusted physical parameter that was perceived to be ‘natural’ by the participant. Therefore, it is reasonable to presume that the level of perceived naturalness of the upper and lower bounds stimuli, relative to the other stimuli in the scenario, was approximately constant across the scenarios. Note that because upper and lower naturalness bounds varied across participants, using the same naturalness bounds for all participants (e.g., the means) would not be appropriate. In order to overcome this problem, in Experiment 2 we tested the same sample of participants of Experiment 1, so that the stimuli used for each participant in Experiment 2 could be obtained from the individual estimates of the upper and lower naturalness bounds provided by the participant in Experiment 1.

3.5 Results and discussion

Separate analyses for the two simulated materials were carried. For each of the 21 possible unordered stimulus pairs, we first computed the probability that one stimulus was judged as more natural than the other. Table 3 shows the probability that the row stimulus was judged as more natural than the column stimulus. These probabilities are estimated across the whole dataset of 120 observations for each pair (i.e., 2 presentation orders ✕ 2 repetitions ✕ 30 participants).

Polystyrene

	***A-NoF*/U**	***A-NoF*/L**	***A-F*/U**	***A-F*/L**	***D*/U**	***D*/L**
***A-NoF*/U**	.500	.400	.550	.417	.458	.425
***A-NoF*/L**		.500	.575	.542	.658	.533
***A-F*/U**			.500	.400	.492	.508
***A-F*/L**				.500	.483	.592
***D*/U**					.500	.433
***D*/L**						.500

Wood

	***A-NoF*/U**	***A-NoF*/L**	***A-F*/U**	***A-F*/L**	***D*/U**	***D*/L**
***A-NoF*/U**	.500	.566	.533	.575	.525	.575
***A-NoF*/L**		.500	.400	.483	.467	.525
***A-F*/U**			.500	.566	.575	.658
***A-F*/L**				.500	.458	.583
***D*/U**					.500	.583

***D*/L**						.500

Table 3. Each cell shows the probability, estimated across the 120 observations for each pair of stimuli in Experiment 2, that the row stimulus was judged to be more natural than the column stimulus. *A-NoF* stands for the acceleration adjustment-frictionless scenario, *A-F* stands for the acceleration adjustment-friction scenario, and *D* stands for the density adjustment scenario. Moreover, U and L stand for the upper and the lower naturalness bounds, respectively.

In order to obtain a general picture of the results from Experiment 2, we calculated, separately for each simulated material, the probability that a stimulus in the *A-NoF* scenario was judged as more natural than a stimulus in the *A-F* scenario, disregarding naturalness bound type (i.e., upper or lower). This probability was estimated from the 480 observations relative to pairs of stimuli belonging to the two scenarios (4 pairs × 2 presentation order × 2 repetitions × 30 participants). The estimated probability was .521 for the polystyrene sphere and .498 for the wooden sphere. With a similar approach, we also computed the probability that a stimulus in the *A-NoF* scenario was judged as more natural compared to a stimulus in the *D* scenario, obtaining .519 for the polystyrene sphere and .569 for the wooden sphere. Lastly, the probability that a stimulus in the *A-F* scenario was judged as more natural than a stimulus in the *D* scenario was .519 for the polystyrene sphere and .523 for the wooden sphere. Overall, these values are very close to .5, suggesting no definite preference for stimuli from a specific scenario. In other words, there appears to be no general preference for vertical falls characterized by the simulated effects of air resistance over vertical falls in a vacuum, even when the motion pattern of the spheres was very similar to the physically correct motion pattern, as in the *D* scenario.

In order to provide an exhaustive test of the effects of bound type (upper vs lower) and scenario on the perceived naturalness of the stimuli, we analyzed the data of Experiment 2 using a *random conjoint measurement* model (Falmagne, 1976; Ho et al., 2008; Knoblauch & Maloney, 2012). In line with the principles of this model, we can denote the two levels of factor *bound* (upper and lower) as b_u and b_l, and the three levels of the factor scenario (*A-NoF*, *A-F*, *D*) as s_{nf}, s_f and s_d. Each stimulus is then represented by a pair (b_i, s_j), where b_i is a level of factor bound and s_j is a level of factor scenario. In each trial of the experiment, two stimuli f_{ij} and $f_{i'j'}$ were presented in a 2-AFC task. Under the assumption that the two factors combine additively to determine the perceived naturalness of the stimuli, the participant's response on each experimental trial can be described as follows:

1) f_{ij} is judged more natural than $f_{i'j'}$ if $(\beta(b_i) + \sigma(s_j)) - (\beta(b_{i'}) + \sigma(s_{j'})) + Z > 0$,
2) $f_{i'j'}$ is judged more natural than f_{ij} if $(\beta(b_i) + \sigma(s_j)) - (\beta(b_{i'}) + \sigma(s_{j'})) + Z < 0$,

where Z is a random noise variable with standard distribution, $\beta(b_i)$ and $\beta(b_{i'})$ are scale values associated with levels b_i and $b_{i'}$ of the factor bound, and $\sigma(s_j)$ and $\sigma(s_{j'})$ are scale values associated with levels s_j and $s_{j'}$ of the factor scenario. In the additive model there are five unknown parameters [$\beta(b_u)$, $\beta(b_l)$, $\sigma(s_{nf})$, $\sigma(s_f)$, $\sigma(s_d)$] which may take different values for the two simulated materials, and which can be estimated through the maximum likelihood method. Because these parameter estimates are determined up to linear transformations, parameters $\beta(b_l)$ and $\sigma(s_{nf})$ were arbitrarily kept fixed at zero in order to reduce the number of model parameters to be estimated. For each simulated material, the additive model was fit to the pooled data because the number of stimuli and repetitions was too small to allow a fit to the individual data.

To test if both experimental factors contributed to the perceived naturalness of the stimuli, we also fit two single-factor models to the data. The bound-only model involves only two parameters [$\beta(b_u)$, $\beta(b_l)$], and it expresses the hypothesis that naturalness judgments are affected by the bound factor alone; symmetrically, the scenario-only model involves three parameters [$\sigma(s_{nf})$, $\sigma(s_f)$, $\sigma(s_d)$], and it expresses the hypothesis that naturalness judgments are affected by the scenario factor alone. In the bound-only model, the parameter $\beta(b_l)$ was set to zero, as well as parameter $\sigma(s_{nf})$ in the scenario-only model. As for the simulated polystyrene sphere, whereas the additive model proved to fit the data significantly better than the scenario-only model ($\chi^2(1) = 21.49$, $p < .001$), the additive model did not fit the data significantly better than the bound-only model ($\chi^2(2) = 1.93$, $p > .10$). This suggests that only the factor bound significantly contributed to the participants' responses. The estimated parameters indicate that the lower naturalness bound stimuli were perceived as slightly more natural than the upper naturalness bound stimuli, $\beta(b_u) = -0.177$, $\beta(b_l) = 0$. As for the simulated wooden sphere, the additive model fitted the data significantly better than both the scenario-only model ($\chi^2(1) = 26.35$, $p < .001$) and the bound-only model ($\chi^2(2) = 8.99$, $p < .05$). This suggests that both factors contributed to the participants' responses. The estimated parameters for the additive model suggest the following findings. First, the upper naturalness bound stimuli were perceived as slightly more natural than the lower naturalness bound stimuli. Second, the *A-F* stimuli were perceived as slightly more natural than the stimuli from the other two scenarios; and third, that the *A-NoF* stimuli were perceived as slightly more natural than the *D* stimuli, ($\sigma(s_{nf}) = 0$, $\sigma(s_f) = 0.042$, $\sigma(s_d) = -0.095$, $\beta(b_u) = 0.197$, $\beta(b_l) = 0$).

Taken together, these results do not provide support to the hypothesis that simulated vertical falls characterized by the effects of air resistance (i.e., *A-F* and *D* scenarios) were perceived as more natural than simulated vertical falls in a vacuum (i.e., *A-NoF* scenario). In other words, the presence or absence of the simulated effects of air resistance does not appear to affect the perceived naturalness of vertical falls of simulated polystyrene or wooden spheres. It is worth noting that this result may partially depend on the fact that, at least in some trials, the difference between the motion patterns of the stimuli from different scenarios was difficult to perceive. The discriminability of the difference between pairs of stimuli in each trial could vary from trial to trial and from individual to individual, depending on the values of the individual estimates of the naturalness bounds. Table 4 provides the discriminability of the simulated falls that were compared in Experiment 2. Specifically, the table shows the percentage difference between the average speeds (in deg/s) associated with respectively the row and the column stimuli. As in Experiment 1, it is tentatively assumed that a difference between the corresponding simulated falls could be perceived when the absolute value of the percentage difference was equal to or larger than 6% [4]. Note that the average speeds refer to the mean naturalness bounds of Experiment 1, therefore these data do not account for the inter-individual variability of the naturalness bounds. Nevertheless, the results suggest that it is unlikely that the lack of a systematic preference for the realistic falls characterized by the presence of the simulated effects of air resistance over the less realistic falls in a vacuum could be due to a lack of perceptual discriminability of the stimuli. Indeed, the percentage differences between the simulated falls corresponding to the mean lower naturalness bounds in the *A-NoF* scenario and the simulated falls corresponding to the mean lower naturalness bounds in the *D* scenario were quite large (i.e., -47.1% and -21.7% for the polystyrene and the wooden sphere, respectively). Despite this, the results of Experiment 2 failed to reveal any systematic preference for the realistic simulated falls in the *D* scenario over the less realistic simulated falls in the *A-NoF* scenario (see Table 3).

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[4] Our interpretation of the results in Table 4 should be taken with caution. For a fixed average speed, the motion profile of a vertical fall in a vacuum differs from the motion profile of a vertical fall in the presence of air resistance. Being dependent upon average speed, the 6% threshold value does not account for differences between the motion profiles of the spheres.

Polystyrene

	***A-NoF*/U**	***A-NoF*/L**	***A-F*/U**	***A-F*/L**	***D*/U**	***D*/L**
***A-NoF*/U**	0%	42.3%	7.1%	48.2%	-.2%	-3.4%
***A-NoF*/L**		0%	-32.9%	4.2%	-42.5%	-47.1%
***A-F*/U**			0%	38.5%	-7.3%	-10.7%
***A-F*/L**				0%	-48.5%	-53.3%
***D*/U**					0%	-3.2%
***D*/L**						0%

Wood

	***A-NoF*/U**	***A-NoF*/L**	***A-F*/U**	***A-F*/L**	***D*/U**	***D*/L**
***A-NoF*/U**	0%	38.5%	.2%	33.2%	8.5%	8.3%
***A-NoF*/L**		0%	-38.2%	-4.0%	-21.7%	-28.0%
***A-F*/U**			0%	32.9%	8.2%	8.0%
***A-F*/L**				0%	-22.8%	-23.0%
***D*/U**					0%	-.2%
***D*/L**						0%

Table 4. Each cell shows the percentage difference between the average speed (in deg/s) associated with the row stimulus and the average speed associated with the column stimulus. The average speeds refer to the mean naturalness bounds from Experiment 1. It is assumed that a difference between a pair of stimuli can be perceived when the absolute values of the percentage difference is ≥ 6%.

3.6 Explorative analysis: effects of formal instruction in physics

Similarly to Experiment 1, an explorative analysis was carried in order to evaluate whether participants' level of education in physics had an effect on their judgments. For each participant we estimated the probability that a stimulus from a realistic scenario (i.e., *A-F* and *D* scenarios) was judged as more natural than a stimulus from the *A-NoF* scenario. Data from both simulated materials were collapsed together. For each participant, the estimated probability was calculated on the 64 pairs involving the comparison between a stimulus from a realistic scenario and a stimulus from the *A-NoF* scenario (8 pairs ╳ 2 presentation order

× 2 materials × 2 repetitions). Figure 7 shows these probability values as a function of the number of years of formal training in physics. Not considering the single participant who reported a total of six years of formal training in physics, we may notice that the level of formal training appears to have a negative effect on the probability to answer ‘more natural’ to the stimuli from the two realistic scenarios. However, the results of this explorative analysis should be taken with caution as they cannot be generalized beyond the sample considered in this study.

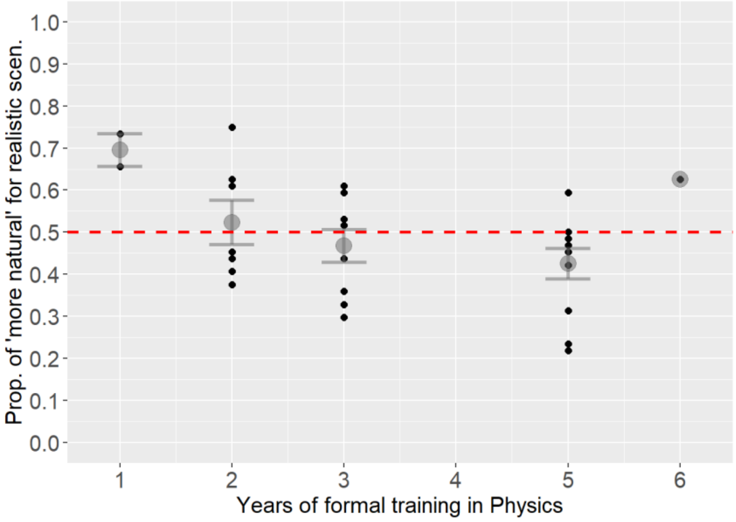

Figure 7. The black dots indicate, for each participant in Experiment 2, the proportion of ‘more natural’ responses for a stimulus from one of the realistic scenarios (i.e., *A-F* and *D*) against one from the unrealistic *A-NoF* scenario, as a function of the participant’s number of years of formal training in physics. Response proportions were averaged across the two simulated materials. The large grey dots correspond to the mean response proportions for each group of participants, the error bars represent the standard error of the mean.

4. Experiment 3

Whereas in Experiments 1 and 2 we focused on the comparison between perceived naturalness judgments and the predictions from Equation 2, in Experiment 3 the predictions from Equation 2 will be compared with imagined (i.e., unseen) vertical falls of simulated wooden and polystyrene spheres.

4.1 Mental simulations of physical events

From an evolutionary perspective, one of the most useful functions of intuitive physics is the generation of predictions about the behavior of physical objects. For instance, in order to decide if we have enough time to cross a road, we have to visually estimate the speed of the approaching cars, integrate this information with previous knowledge (e.g., “do cars typically slow down when they arrive close to the crosswalk?”, “how fast can I walk?”), and then take a decision. Because these kinds of decisions have to be taken very quickly, the processes underlying them are largely automatic and unconscious. However, laypeople may also engage in conscious, slow, and attention-demanding mental simulation processes. A relatively simple example of such simulation process is the mental rotation of 3D figures (Shepard, 1984). Mental simulations, however, may also be used in more complex physical situations, such as predicting the behavior of a liquid contained in a glass that is progressively tilted (Schwartz, 1999; Schwartz & Black, 1999), or predicting the stability of towers of 3D blocks (Battaglia et al., 2013; Hamrick et al., 2011). According to Shepard (1994), mental simulations would be based on an internalized representation of universal geometric principles, whereas Shepard (1994) himself argued against the hypothesis that mental simulations are driven by internalized physical principles (see also Hecht, 2001). However, at odds with this hypothesis, Battaglia et al. (2013; see also Kubricht et al., 2017; Ullman et al., 2017) suggested that mental simulations of physical phenomena can be described in terms of a Bayesian model that integrates perceptual information with internalized Newtonian principles.

A relatively small number of studies have directly focused on the investigation of mental simulations of physical phenomena. For instance, Schwartz and Black (1999) presented participants with a water-pouring task, in which they were asked to estimate how much some glasses of various shapes had to be tilted in order to allow the liquid inside them to reach their edges. In a mental simulation condition, participants were allowed to imagine the tilting of the glass and to visualize the motion of the liquid, whereas in an abstract prediction condition they had to rely only on explicit reasoning processes. Whereas in the mental simulation condition the participants’ responses were found to be consistent with the predictions from physics, in the abstract prediction condition the participants tended to overestimate the tilt of short wide glasses and to underestimate the tilt of tall narrow glasses. Interestingly, Schwartz (1999) also found that the material properties of the liquid play an important role in mental simulations, as participants correctly imagined that after the glass was tilted a dense fluid like molasses reacted to the tilting more slowly than a less dense fluid like water. Overall, these results appear to suggest that mental simulations have access to internalized representations of physical principles that are instead inaccessible to explicit reasoning processes (see also Frick et al., 2005).

To the best of our knowledge, three studies have explored the mental simulation of gravitational motion. Huber and Krist (2004) presented a group of participants with a small-scale simulated scenario that showed a ball leaning on a flat horizontal surface. The surface was located at some vertical distance from the ground. A schematic drawing of a house was present in the background, so to provide cues about the size of the objects represented in the scenario. In the mental imagery condition, participants could see the ball that started rolling horizontally until it reached the edge of the surface. An opaque occluder was present next to the edge of the surface, to occlude the motion of the ball when it fell off the surface. Participants could also see a target on the ground, at a variable horizontal distance from the edge of the surface. The horizontal speed of the ball was regulated so that the ball always fell on the target. The simulated vertical height of the surface and the simulated horizontal distance of the target from the surface were manipulated according to a factorial design. Participants were instructed to imagine the falling motion of the ball, and to press a button when the sphere had reached the target. Results showed that participants' time-to-contact estimations were fairly accurate in this mental imagery condition, as they were correctly affected by the height of the surface and not by the horizontal distance of the target. By contrast, in a static version of the task that did not involve mental imagery, participants' responses were also affected by the physically irrelevant variable of the horizontal distance of the target from the surface. These results appear to suggest that mental imagery activated an accurate physics-based knowledge of projectile motion that was otherwise inaccessible to abstract reasoning processes. However, this conclusion is at odds with the results of a study by Gravano et al. (2017). In that study, participants had to imagine throwing a ball against a ceiling varying in height, and to catch it on rebound. The kinematic features of the imagined trajectory of the ball were inferred from measures of the speed and timing of the throwing and catching actions. Participants were also instructed to imagine performing the throwing action either in a terrestrial environment, that is, under the influence of Earth's gravity (i.e., the $1g$ condition), or in space, that is, under microgravity conditions (i.e., the $0g$ condition). Surprisingly, both in the $1g$ and in the $0g$ conditions, the timing of the catching actions was consistent with an imagined constant slow-speed motion, rather than with an imagined uniform deceleration followed by uniform acceleration. Similar results were obtained when participants had to imagine throwing the ball upwards without hitting the ceiling. These results run against the hypothesis that mental simulations of gravitational motion have access to an internalized representation of gravitational acceleration. Rather, the results suggest that laypeople rely on simplified kinematic representations by which objects move at slow constant speed even when they are under the influence of gravitational acceleration. In a recent study by Bratzke and Ulrich (2021) participants were asked to imagine the vertical fall of an apple. In a first task, they were presented with different falling time durations and were required to estimate the corresponding falling height. Conversely, in a second task, they were presented with different falling heights and had to estimate the corresponding falling time. Falling heights were defined through a marker presented next to the picture of a real tower with which participants were familiar and that acted as a reference frame. At odds with Huber and Krist (2004) but consistently with Gravano et el. (2017), imagined falls were consistent in both tasks with a slow constant velocity motion rather than obeying Equation 2. However, it cannot be excluded that the observed discrepancies between participants' responses and actual motion in Bratzke and Ulrich's (2021) study might be due to the difficulty of the task. Participants' responses in the height estimation task might indeed reflect abstract reasoning rather than mental imagery of vertical falls, in that the starting point of the fall had to be estimated only after the presentation of the target falling time duration. Moreover, in both tasks the participants had to scale their representations of vertical fall to the remembered height of the tower.

4.2 Outline of Experiment 3

In the light of the contrasting results emerging from previous studies (Bratzke & Ulrich, 2021; Gravano et al., 2017; Huber & Krist, 2004), Experiment 3 aimed at further exploring the mental simulation of vertical motion through the comparison between the spatio-temporal features of mental simulations of vertical falls and the predictions from Equation 2. Differently from Experiments 1 and 2, in this experiment participants were presented only with a very short initial part of the vertical trajectory of simulated wooden and polystyrene spheres, while the remaining part of the fall was hidden by an occluder. Participants were asked to estimate the position of the sphere behind the occluder after variable time intervals from the beginning of the fall. This approach allowed us to map the imagined position of the sphere as a function of time, and to directly compare the estimated time-position function with the predictions from Equation 2.[5]

Experiment 3 also tested the possible influence of the simulated materials of the spheres on their imagined vertical falls, a topic that has remained unexplored in previous studies on mental simulations of gravitational motion (Bratzke & Ulrich, 2021; Gravano et al., 2017; Huber & Krist, 2004). After the results of Experiment 1 showed that the implied weights of the simulated spheres exert a strong influence on the physical parameters of the vertical falls that are perceived to be natural by participants, we believe that it is worth testing if the implied weights also have an effect on the motion pattern of imagined vertical falls.

4.3 Participants

Thirty participants (12 males, mean age = 23.3 years, SD = 2.34 years) took part in Experiment 3. They were all students from the University of Padova. None of them had participated in Experiment 1 and 2. On average, they had studied physics at school for 3.63 years (SD = 1.56 years). All of them were naive to the purpose of the experiment, and reported normal or corrected-to-normal visual acuity as well as normal hearing abilities. At the end of the experiment, they received 5€ of compensation for their participation. We decided to test 30 participants for the sake of comparison between the results of Experiments 1 and 3.

4.4 Apparatus

The apparatus was the same as in Experiments 1 and 2 (see Figure 2).

4.5 Stimuli and Procedure

The stimuli were the same as in Experiment 1, except that an opaque gray long rectangle of 12.8 × 148.5 cm (from now on the occluder) appeared on the projected screen, with its vertical axis aligned to the vertical axis

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[5] This task bears some resemblance to prediction-motion tasks (Battaglini & Mioni, 2019; Battaglini et al., 2013; Makin, 2018; Vicovaro et al., 2019). However, in Experiment 3 participants were shown a very brief part of the motion of the target object (i.e., the sphere), whereas in prediction-motion tasks the visible part of motion is typically long enough to allow the extrapolation of the speed of the target object.

of the screen and its bottom side aligned to the lower margin of the screen. At the beginning of each trial a simulated polystyrene or wooden sphere was presented centered 5.5 cm below the upper limit of the screen and 2.6 cm above the top side of the occluder. There was only a .1 cm distance between the lower margin of the simulated sphere and the top side of the occluder, meaning that the simulated sphere gradually disappeared behind the occluder immediately after it started falling downward.

Before starting the experiment, participants were provided with an informed consent form with the instructions for the task and were presented with the real wooden and polystyrene spheres, as in Experiments 1 and 2. Then, they were provided with a mouse device that controlled a pointer on the screen (see below). Participants had to keep the mouse device on their legs, moving it with their favorite hand. At the beginning of each trial, apart from the simulated sphere and the occluder, a white pointer appeared in the upper-right part of the screen. After a time interval randomly sampled from a normal distribution with mean 1 s and standard deviation .5 s, the simulated sphere started falling vertically downward coherently with Equation 2, soon disappearing behind the occluder. The remaining part of the fall was hidden by the occluder. Participants were asked to imagine the falling sphere as a real sphere made of that material and falling from that height. A brief beep (duration: .0167 s, frequency: 1000 Hz) was presented after an interval of .2, .4, .6, .8 or 1.0 s from the starting of the fall. Participants were instructed to click on the exact point of the screen where they thought the center of the sphere would have been, should the sphere not be hidden by the occluder. The vertical coordinate of the selected point was used to compute the imagined distance of the center of the simulated sphere from the starting point of the fall at the onset of the beep. Participants were instructed that, if they thought that the sphere was already below the lower limit of the screen when they heard the beep, they had to click in the upper-right part of the screen (these were coded as ‘below’ responses). We recall that, as in Experiments 1 and 2, the distance between the center of the simulated sphere at the starting point of the fall and the lower limit of the screen was 1.511 m. The dotted curves in Figure 9 represent the distance from the starting point of the fall of the polystyrene and wooden spheres as a function of time, calculated according to Equation 2. The curves show that after .6, .8 and 1.0 s, the center of the simulated spheres would be already below the lower limit of the screen.

Each participant was randomly presented with a total of 200 experimental trials, given by a 2 (Simulated material) × 5 (Time interval) × 20 (Repetitions) factorial design. Before starting the experiment, 20 randomly selected trials were presented to familiarize the participant with the experimental procedure.

4.6 Results and discussion

Figure 8 shows the percentage of ‘below’ responses as a function of factors time and simulated material. The ‘below’ responses were only 1.67% of the 6000 total responses (200 trials ✕ 30 participants), with a peak of 9.67% for the simulated wooden sphere at the longest time interval (i.e., 1.0 s). These results show that, with a few exceptions, the estimated vertical position of the sphere was still within the screen limits even after 1.0 s from the beginning of the fall. Note that, in the following steps of the analysis, ‘below’ responses were replaced with the highest possible value of estimated vertical distance, that is, the distance between the starting point of the fall and the lower limit of the screen (i.e., 1.511 m).

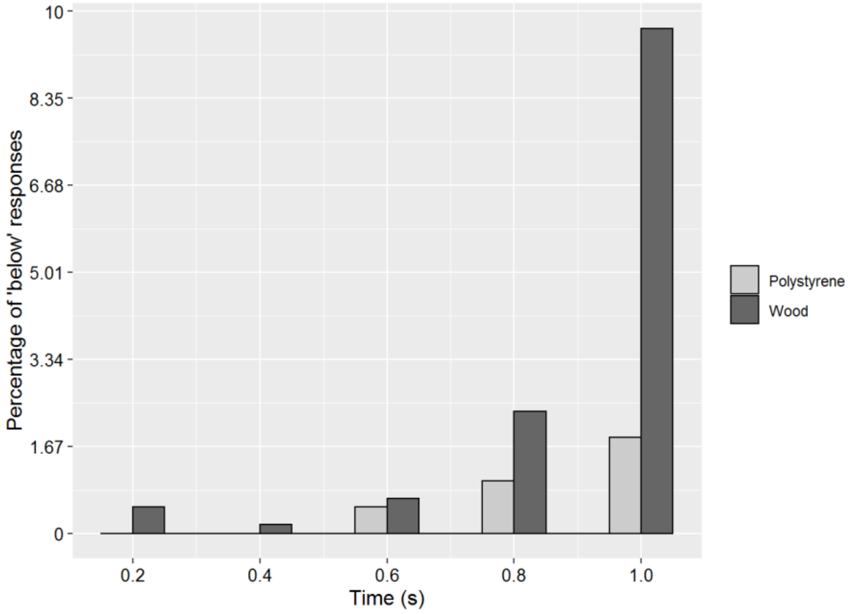

Figure 8. Percentage of ‘below’ responses in Experiment 3 calculated on a total of 600 trials (20 repetitions ✕ 30 participants) for each time interval from the beginning of the fall and each simulated material.

The thick solid curves in Figure 9 represent the estimated vertical distance of the simulated sphere from the starting point of the fall as a function of the time interval, averaged across participants. The left (right) panel shows the data for the simulated polystyrene (wooden) sphere. The individual trends are represented with thin solid curves. The dotted curves represent the physically correct time-position function as by Equation 2. A first important result from Figure 9 is that, differently from the physically correct time-position functions that exhibit a clear positive quadratic trend, the subjective curves appear to exhibit only a linear trend. This suggests that the simulated spheres were imagined falling at constant speed, rather than with an accelerated motion as predicted by Equation 2. In other words, the imagined motion of the spheres does not appear to take gravitational acceleration into account, which is clearly at odds with the hypothesis that mental simulations of gravitational motion have access to internalized representation of Earth's gravity (see also Bratzke & Ulrich, 2021; Gravano et al., 2017).

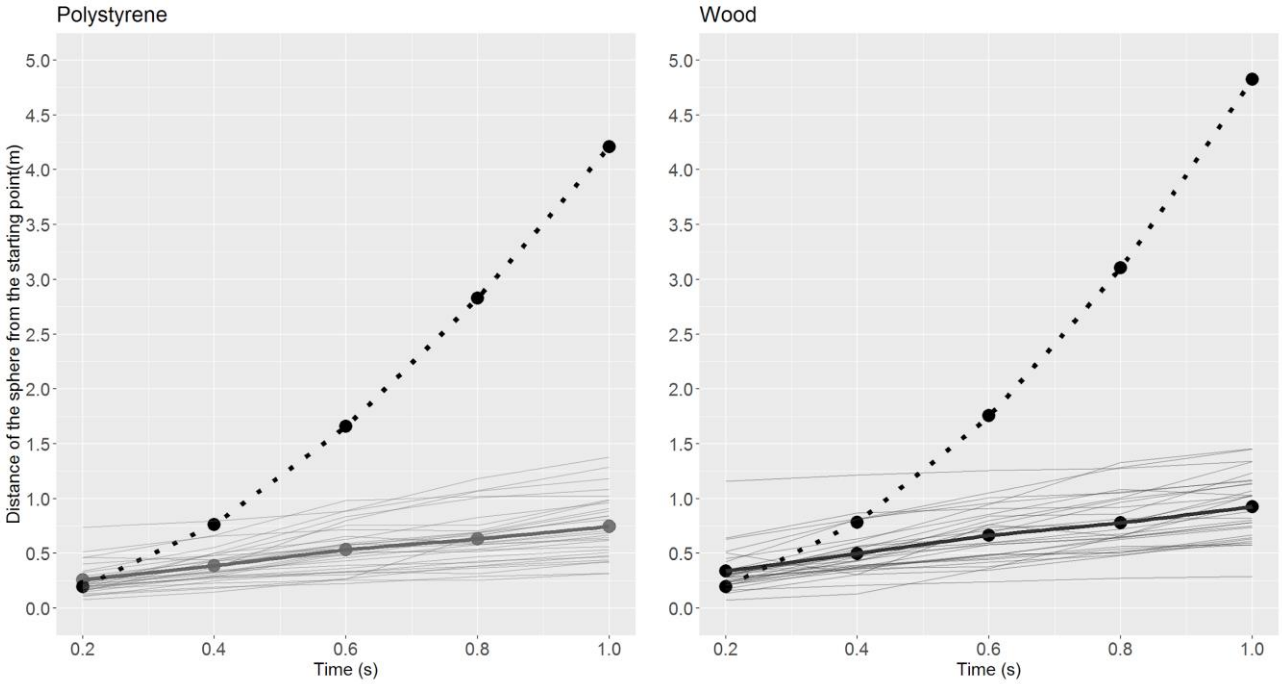

Figure 9. The solid thick lines represent the mean estimated distance of the center of the simulated polystyrene sphere (left panel) or wooden sphere (right panel) as a function of the time interval between the starting of the fall and the beep sound. The thin solid lines represent the individual trends. The dotted lines show the physically correct distance, as predicted from Equation 2.

We analyzed the estimated vertical distance of the simulated spheres from the starting point of the fall using a linear mixed effects model. As fixed effects we entered a linear and a quadratic component for the time interval, the simulated material, the interaction between the linear component of the time interval and the simulated material, and the interaction between the quadratic component of the time interval and the simulated material. The random effects were by-subject estimates of the simulated sphere position at each time interval[6]. This model fitted the data significantly better than a model with random intercept only ($\chi^2(1) = 775.24$, $p < .001$). The effects of the linear component of time interval were statistically significant ($b = .612$, $SE_b = .032$, $t(140.8) = 19.1$, $p < .001$) as well as the effects of simulated material ($b_{wood} = .13$, $SE_b = .008$, $t(5847) = 15.85$, $p < .001$). The effects of the quadratic component of time interval were not statistically significant ($b = -.146$, $SE_b = .135$, $t(140.8) = -1.08$, $p > .10$). Note that imagined acceleration would imply a statistically significant positive quadratic component of the time interval, whereas the results show a non-significant negative quadratic component. Importantly, the interaction between the linear component of the time interval and the simulated material was statistically significant ($b_{time/wood} = .115$, $SE_b = .019$, $t(5847) = 6.16$, $p < .001$), which means that the simulated wooden sphere was imagined to fall faster than the simulated polystyrene sphere. The interaction between the quadratic component of time interval and simulated material was not statistically significant ($b_{time\text{^}2/wood} = .002$, $SE_b = .079$, $t(5847) = .03$, $p > .10$)[7]. The estimated coefficients indicate that the average imagined speeds of the simulated polystyrene and wooden sphere were .612 m/s and .727 m/s, respectively. An important methodological note is that, in trials in which participants provided ‘below’ responses, the estimated imagined vertical distance of the sphere from the starting point of the fall (1.511 m) was necessarily underestimated with respect to the actual imagined distance. Since the ‘below’ responses were most frequent for the simulated wooden sphere and for the longest time intervals (see Figure 8), it is likely that the above-reported estimated speed of the simulated wooden sphere is a slight underestimation with respect to the real imagined speed.

Apart from the lack of acceleration, the imagined motion patterns of the simulated spheres also differed from the physically correct motion pattern in average speed. According to Equation 2, in the time interval between 0 and 1 s the average falling speeds of the polystyrene and the wooden sphere would be 4.208 m/s and 4.824 m/s, respectively. Therefore, the imagined speeds of the simulated polystyrene and wooden spheres (i.e., .612 m/s and .727 m/s, respectively) were about seven times smaller than the corresponding physical speeds. In other words, the imagined falling speeds were much slower than the

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[6] We used the *lmer* function from R package lme4 (Bates et al., 2015). The linear mixed effects model was specified as follows: *y ~ (time + I(time^2)) * material + (1|id/time)*, where *y* is the estimated vertical position of the sphere, *time* is the centred variable coding the time interval from the beginning of the fall, *material* is the variable coding the simulated material and *id* is the participant’s identification code.

[7] We also performed a two-way ANOVA on estimated distance, which showed that the main effects of time interval were statistically significant ($F(4,116) = 118.33$, $p < .001$, $\eta_G^2 = .41$), as well the effects of the simulated material ($F(1,29) = 31.19$, $p < .001$, $\eta_G^2 = .076$) and of the interaction ($F(4,116) = 5.38$, $p < .005$, $\eta_G^2 = .005$),

physically correct average speed (see also Gravano et al., 2017). We also compared the effects of implied weight on physical and imagined speeds. The physical speed of the wooden sphere would be 1.146 times larger than that of the polystyrene sphere, whereas the imagined speed of the simulated wooden sphere was 1.188 times larger than that of the simulated polystyrene sphere. This indicates that implied weight had a slightly larger effect on imagined than on physical speeds. This comparison should be taken with caution both because of the large difference between physical and imagined speeds, and because the imagined speed of the simulated wooden sphere was probably slightly underestimated due to the presence of a non-negligible percentage of ‘below’ responses for the longest time interval. In other words, the effects of implied weight on the imagined falling speeds are probably slightly larger than suggested by the estimated coefficients. Nevertheless, an important result emerging from Experiment 3 is that the implied weight affected the imagined falling speed of the simulated spheres. Taken together, the results of Experiment 3 provide strong evidence against the hypothesis that mental simulations of gravitational motion are driven by an internalized representation of Earth’s gravity (see also Bratzke & Ulrich, 2021; Gravano et al., 2017).

A possible limitation of Experiment 3 is that, despite the fact that participants were informed that the sphere could go below the lower limit of the occluder, they may have tacitly assumed that such lower limit corresponded to the boundary of the response scale. In other words, the responses might have been (consciously or unconsciously) adapted to the length of the occluder, which could partially explain the large underestimation of the imagined falling speed. However, some of the participants were clearly aware of the possibility that the simulated sphere could go below the lower limit of the occluder. Indeed, seven participants provided at least 25% of ‘below’ responses for the simulated wooden sphere at the 1 s interval (one participant provided 70% of ‘below’ responses). However, as shown in the right panel of Figure 9, all of the 30 participants, including those who provided a relatively large number of ‘below’ responses, tended to provide large underestimations of the distance travelled by the simulated spheres after .6 s and .8 s[8]. This likely suggests that the response bias cannot fully account for the results of Experiment 3, although we acknowledge that it may have contributed to some extent.

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[8] We would like to add an anecdotal observation from our own experience in this regard. Although as experimenters we are aware that the sphere would be already below the lower limit of the screen after .6 s or .8 s, our intuitive predictions of the position of the sphere at different time intervals would be substantially consistent with the participants’ average responses (Figure 9). We are thus inclined to exclude that the underestimation of the imagined falling speed is an artefact due to the experimental procedure, although we cannot exclude that we unconsciously adjusted our predictions to the length of the occluder.

Comparing the results of Experiments 1 and 3 we note that, in the *A-F* scenario of Experiment 1, in the interval between 0 and 1 s the average speed of the motion corresponding to the lower naturalness bounds was 1.847 m/s for the simulated polystyrene sphere and 3.108 m/s for the simulated wooden sphere. This means that the imagined speeds were at least three-to-four times smaller than the average speeds of perceptually natural falls. In other words, if the imagined vertical falls were actually presented to the participants of Experiment 1, then they would have been judged as clearly unnatural (i.e., too slow)[9]. This finding highlights a discrepancy between visually perceived and imagined vertical falls (for further considerations see the general discussion). As regards the effects of implied weight on imagined and perceived vertical falls, the simulated material proved to exert a stronger influence on perceived naturalness than on imagined falls (i.e., average speed ratio 1.683 vs. 1.188). However, we add a note of caution concerning the interpretation of the comparison between the results of Experiments 1 and 3, both because the results of Experiment 3 might be partially affected by the response bias discussed above, and because in Experiment 1 the participants could not make any adjustments that would have resulted in uniform speed simulated falls.

As for the possible effects of formal training in physics on participants' responses, the thin solid curves in Figure 9 show a marked consistency across participants as regards the imagined motion pattern of the simulated spheres. None of these curves is consistent with the physically correct motion pattern (dotted curves), which suggests that, at least for this sample of participants, formal training in physics did not have a clear influence on imagined vertical falls. Individual data were analyzed by fitting a linear model to individual estimates of vertical distance (200 trials in total). Considered predictors were a linear and a quadratic component for the time interval, the simulated material, and the interactions between both linear and quadratic components of the time interval and the simulated material. Results showed that the linear component of the time interval was statistically significant for all participants, whereas the quadratic component was statistically significant for only seven participants. Two of these seven participants showed a positive coefficient for the quadratic component, indicating that only these participants imagined a positively accelerated vertical fall. One of these participants had studied physics at school for two years, the other for

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[9] In the position-velocity graphs of Figure 4, the imagined vertical falls of Experiment 3 would correspond to a straight line that, after an instantaneous acceleration, runs parallel to the horizontal axis and intersects the vertical axis at .612 m/s (polystyrene) or at .727 m/s (wood).

five years. The effects of the simulated material were statistically significant for 20 participants; on average, these participants had studied physics at school for 3.95 years (SD = 1.67 years), against a mean of 3 years (SD = 1.15 years) for the participants who did not show a significant effect of simulated material. The interaction between the linear component of the time interval and the simulated material was statistically significant for 10 participants, who had studied physics at school for a mean of 3.6 years (SD = 1.78 years), against a mean of 3.65 years (SD = 1.5 years) for the participants who did not show a significant interaction effect. Only one participant who had studied physics at school for three years showed a statistically significant interaction between the quadratic component of the time interval and the simulated material. Overall, the results of this analysis show no systematic effect of formal instruction in physics on participants' responses.

5. General Discussion

In three experiments we explored the intuitive physics of gravitational motion. Consistently with the results of a previous study by Vicovaro et al. (2019), the results of Experiment 1 support the hypothesis of a weight-based perceptual representation of gravitational motion, by which a relatively light object such as a polystyrene sphere should fall much slower than a heavier object such as a wooden sphere. The results of Experiment 1 extend the results of Vicovaro et al. (2019) in two important respects. First, they show that weight affects the perceived naturalness of somewhat unrealistic falls in a vacuum as well as that of realistic falls characterized by the simulated effects of air resistance. Second, Experiment 1 provides precise quantitative measures of the physical parameters (i.e., gravitational acceleration and density of the medium) giving rise to perceptually natural falls. It is worth noting that the results of Experiment 1 do not suggest complete ignorance of participants of the physical characteristics of gravitational motion. Indeed, for the simulated wooden sphere the positions of the naturalness intervals were quite accurate, that is, consistent with the physically correct values of gravitational acceleration or density of the medium. On one hand, this suggests that participants had a fairly realistic representation of the vertical falling motion of a wooden sphere. On the other hand, it suggests that it is unlikely that the lack of accuracy in the position of the naturalness intervals for the simulated polystyrene sphere could be due to a bias related to the experimental procedure, otherwise this bias would have emerged also for the simulated wooden sphere. Rather, as we will argue in more details below, the results are consistent with the hypothesis that participants' responses were driven by a heuristic weight-based representation of gravitational motion. As regards the results of Experiment 2, to the best of our knowledge they provide the first evidence that people do not have any clear preference for realistic falls characterized by the simulated effects of air drag over less realistic falls in a vacuum, even when they can see the difference between the two types of fall. Lastly, consistently with previous studies (Bratzke & Ulrich, 2021; Gravano et al., 2017), the results of Experiment 3 support the hypothesis of a strong underestimation of the imagined speed of vertical falls, while also providing new evidence of an effect of weight on imagined falling speed.

Importantly, the influence of weight on perceptual judgments of the naturalness of simulated falls does not appear to be due to a lack of realism of the experimental stimuli, which is often deemed as one of the major causes of the lack of accuracy in intuitive physics tasks (Hamrick et al., 2011; Kubricht et al., 2017; Vicovaro, 2021). First, unlike previous studies, the participants were presented with realistic, real-scale representations of real objects that they could manipulate before the experimental task. Second, the effects of simulated material emerged independently of the presence or absence of the simulated effects of air drag. It can still be argued that the experimental setting was very different from a real life scenario, and that the stimuli were virtual simulations with limited contextual information projected on a flat screen. In other words, it can be argued that correct representations of gravitational motion would require a more ecologically valid setting in order to emerge. This hypothesis certainly deserves to be further explored in future studies, however we would like to remark that, with respect to the stimuli used in previous studies on the intuitive physics of gravitational motion, the stimuli that we used in our experiments constitute one step forward towards ecological validity.

5.1 The weight-speed heuristic

The results of Experiment 1 showed a strong effect of the implied masses of objects on the physical parameters that are perceived as 'natural' for vertical falls, and the results of Experiment 3 showed that implied masses also have an effect on the imagined falling motion of objects. These results appear to support the hypothesis that the intuitive physics of gravitational motion is driven by a weight-speed heuristic according to which the falling speed of objects is tightly related with weight. This heuristic appears to be deeply rooted in the cognitive system, as it affects not only perceptual judgments of the naturalness of simulated vertical falls but, to a lesser extent, also mental simulations of vertical falls. A side result of Experiment 1 is that the magnitude of the effects of simulated material on the positions of the naturalness intervals was consistent at the individual level across all three scenarios. This suggests that the weight-speed heuristic was consistently used throughout the experiment. Interestingly, the effects of simulated material on participants' responses appear not to be affected by the level of formal training in physics, at least for the samples of participants that we tested in Experiments 1 and 3.

In general terms, heuristics are useful simplifications of normative rules. What are then the origins of the weight-speed heuristic? In line with Rohrer (2002), we speculate that it might originate from the externalization of body dynamics (see also Hecht, 2001; Vicovaro, 2014). Specifically, the weight-speed heuristic might be a special case of the force-speed heuristic, according to which the speed of an object in a given direction increases with the force exerted by the object (or exerted on the object) in that direction (Clement, 1982; diSessa, 1993; White, 2012). In an environment characterized by the ubiquitous presence of friction, this heuristic allows to make correct predictions in the large majority of cases. For instance, after a kick, a ball moves in the direction of the kick (net of the possible effects of spin), with a speed proportional to the force of the kick. Similarly, an object that is held by a hand exerts on the hand a downward force proportional to its mass. This force is its weight (i.e., $W = mg$, where g is the gravitational acceleration). Laypeople might use this perceived force to predict the subsequent speed of the object once the object itself is released. In the case of a free fall, they might imagine the presence of an equivalent weight force. In doing so, the force-speed heuristic would arise as the transfer of the force perceived in the static condition as the main drive of the dynamic condition. In other words, our hypothesis is that the weight-speed heuristic might result from the overgeneralization of the force-speed heuristic.

5.2 Visual perception and mental imagery of vertical falls

One of the most useful functions of intuitive physics is that of generating predictions about the behavior of objects through mental simulations of physical events. Therefore, mental imagery of physical phenomena constitutes an interesting and still underexplored domain. In this regard, some authors have suggested that mental simulations mimic visual perception of physical phenomena (Frick et al., 2005; Gravano et al., 2017; Huber & Krist, 2004), that is, mental simulations would be based on memory traces of visually perceived physical phenomena. However, the comparison between the results of Experiments 1 and 3 suggests that this might not necessarily be the case. Mental simulations of vertical falls were much slower and less affected by simulated material with respect to perceptual judgments of the naturalness of vertical falls.

A possible speculative hypothesis is that mental simulation might be based on a slow speed prior, rather than on a memory trace of previously perceived vertical falls. Stocker and Simoncelli (2006) suggested that visual speed perception relies on the Bayesian integration of sensory information about the actual speed of a target and a slow speed prior, which typically leads to an underestimation of the perceived speed of the target. When no sensory information about the speed of the target is available as in the case of mental imagery, the cognitive system might rely on this slow speed prior, generating an imagined slow-motion vertical fall. Intriguingly, the results of Experiment 3 also suggest that the slow speed prior might be integrated with a weight-speed prior, such that a relatively heavy object is imagined falling slightly faster than a relatively light object. In addition, the results of Experiment 3 appear to rule out the possibility that mental simulations of vertical fall may be based on an internal representation of Earth’s gravity (see also Bratzke & Ulrich, 2021; Gravano et al., 2017).

5.3 Conclusions and future directions

According to the internalization perspective, cognitive representation of physical phenomena would be driven by internalized physical laws (Battaglia et al., 2013; Kubricht et al., 2017; Ullman et al., 2017). In line with this hypothesis, if perceptual noise and uncertainty about the relevant physical parameters are taken into account, then laypeople’s predictions about physical phenomena are substantially consistent with predictions from physical laws. The internalization hypothesis postulates that accurate performance in intuitive physics tasks is more likely to emerge in ecologically valid experimental conditions. However, the results of the current experiments suggest that perceptual judgements and mental simulations of vertical falls were not based on an internalized representation of Equation 2. This finding cannot be easily attributed to participants' lack of familiarity with the physical phenomenon in question, or to lack of realism of the experimental stimuli. Rather, a possible explanation for this finding is that perceptual judgments and mental simulations of vertical falls rely on a weight-based heuristic representation of gravitational motion.

It is however worth noting that, in Experiment 1, participants exhibited fairly accurate representations of the physical parameters for the wooden sphere, whereas they showed inaccurate representations of the parameters for the polystyrene sphere. In this regard, it can be hypothesized that internalization of physical parameters occurs only for physical objects and events the participants are particularly familiar with. This hypothesis is supported by the results of some studies showing that people tend to perform better in intuitive physics tasks involving concrete and familiar physical events, rather than in tasks involving the abstract representation of the same events (Kaiser, Jonides, & Alexander, 1986; Masin et al., 2014). In the current context, it can be speculated that a sub-optimal heuristic was used in the case of the polystyrene sphere but not in the case of the wooden sphere because the falling objects with which participants are probably most familiar (e.g., sports balls) are characterized by physical weights that are more similar to that of a wooden sphere than to that of a polystyrene sphere. In other words, correct internalized representations of falling motion might be available for objects whose weights are similar to those of falling objects with which people are familiar, whereas heuristics might be used for objects with more 'atypical' weights. This hypothesis is worthy of being explored in future studies, for instance, by exploring if the level of accuracy of the representations of the falling motion of objects decreases as the weight of the falling object deviates from the range of 'typical' weights.

Admittedly, neither the internalization nor the heuristic perspective appear to provide an exhaustive account of intuitive physics (see Vicovaro, 2021). However, the results of our experiments make the pendulum swing (provisionally) on the side of the heuristic perspective. As it has been emphasized by Hamrick et al. (2011; see also Kubricht et al., 2017), one limit of the heuristic perspective is that, more often than not, heuristic models of intuitive physics are not specific enough to provide precise quantitative predictions about participants' responses in intuitive physics tasks. Indeed, even if the weight-speed heuristic can provide a qualitative account of the results, it is not sufficiently specific to make exact quantitative predictions. Therefore, a more precise quantitative definition of the relationship between perceived downward force (i.e. perceived weight) and predicted falling speed remains an intriguing challenge for future studies.

Although these results provide further support to the hypothesis that perceptual and cognitive representations of gravitational motion are driven by heuristics rather than by internalized representations of Earth’s gravity (Gravano et al., 2017; Zago & Lacquaniti, 2005), previous studies suggest that the motor system may instead rely on internalized representations of gravitational acceleration. Specifically, empirical evidence indicates that accurate internalized representations of *g* drive both the manual interception of objects falling vertically downward (McIntyre et al., 2001; Zago et al., 2008; cf. Baurès et al., 2007; Zhao & Warren, 2015) and the ocular pursuit of targets on parabolic trajectories (Jörges & López-Moliner, 2019). This appears to suggest that motor and cognitive system rely on different representations of the physical world (Zago & Lacquaniti, 2005). However, use of an internalized model of gravitational acceleration or of sub-optimal heuristics might also depend on the amount of visual information available to observers. Indeed, support for the internalization hypothesis mainly comes from studies in which the motion of a target was extrapolated from the visible part of its trajectory (e.g., Jörges & López-Moliner, 2019; McIntyre et al., 2001; Zago et al., 2008), whereas support for the heuristic hypothesis mainly comes from studies in which the whole trajectory of the target had to be imagined (Bratzke & Ulrich, 2021; Gravano et al., 2017; see also the results of our Experiment 3).

To conclude, our exploratory analyses did not show any positive relationship between the number of years of formal training in physics and the accuracy of participants’ responses in the three experiments. This finding is partially inconsistent with the results of previous studies showing positive effects of formal training in physics on performance in elementary mechanics problems (e.g., predicting the trajectory of a ball exiting from a curvilinear tube; see Cooke & Breedin, 1994; McCloskey et al., 1980; McCloskey & Kohl, 1983). However, the results of the current study are consistent with those of a previous study by Sequeira and Leite (1991), who found that 52% of a sample of fourth-year university physics students believed that in a vacuum a heavy ball would fall faster than a light ball (i.e., these students reasoned according to the mass-speed belief). Taken together, the results of our current experiments and those reported by Sequeira and Leite (1991) appear to provide support to the hypothesis that the understanding of the physics of gravitational motion is relatively impervious to formal training in physics. However, a more systematic test of this hypothesis would require a direct comparison between different samples of participants characterized by different amounts of formal training in physics.

Students' troubles in the learning of physics are often related to the fact that they start physics courses with their own misconceptions about physical events, and to the fact that the new notions that are presented by teachers tend to be distorted and accommodated to these misconceptions (e.g., Carey, 1986; McDermott, 1991). Therefore, effective teaching programs should first be aimed at correcting the students' previous misconceptions. Under this perspective, the relationship between the mass of objects and their falling motion is a complex issue that needs to be specifically addressed by physics teachers. Perhaps, teaching of the physics of gravitational motion would benefit of a careful evaluation of the origins of students' misconceptions. If our hypothesis that misconceptions originate from the overgeneralization of a force-speed heuristic proved to be correct, then teachers might try to emphasize the reason why there is no relationship between weight (i.e., the force exerted by objects towards the centre of gravitational attraction) and falling speed. The actual effectiveness of this strategy should also be the matter for future studies.

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Data availability statement

All the raw data from the experiments are available as Supplementary Materials.

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