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Intuitive physics of gravitational motion as shown by perceptual judgment and prediction-motion tasks

Michele Vicovaro[a,*], Stefano Noventa[b], Luca Battaglini[a]

[a] Department of General Psychology, University of Padova, Italy
[b] Methods Center, University of Tübingen, Germany

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ABSTRACT

In Experiment 1, we explored participants' perceptual knowledge of vertical fall by presenting them with virtually simulated polystyrene or wooden spheres falling to the ground from about two meters high. Participants rated the perceived naturalness of the motion. Besides the implied mass of the sphere, we manipulated the motion pattern (i.e., uniform acceleration vs. uniform velocity), and the magnitude of acceleration or velocity. Results show that relatively low values of acceleration or velocity were judged as natural for the polystyrene sphere, whereas relatively high values of acceleration or velocity were judged as natural for the wooden sphere. In Experiment 2, the same stimuli of Experiment 1 were used, but the sphere disappeared behind an invisible occluder at some point of its trajectory. Participants were asked to predict the time-to-contact (TTC) of the sphere with the ground by pressing a key at the exact time of impact of the lower edge of the sphere with the floor of the room. Results show that the estimated TTC for the simulated wooden sphere was slightly but consistently smaller than the estimated TTC for the simulated polystyrene sphere. The influence of the implied mass on participants' responses might be the manifestation of two processes, namely an explicit 'heavy-fast, light-slow' heuristic, and/or an implicit, automatic association between mass and falling speed.

1. Introduction

Since gravitational force is a constant presence in our everyday life experience, one might expect that people should have an accurate knowledge of how gravity affects the motion of objects. Yet, if it were so, it wouldn't have taken several centuries from Aristotle's ideas to Galilei's experimentation to shed light on the physical phenomenon (see, e.g., Darling, 2006). Research in the field of intuitive physics has shown that people do not have a good intuitive understanding of the physics of gravitational motion. Shanon (1976) showed that a significant minority of a group of students incorrectly believed that objects fall at a constant speed rather than with uniform acceleration as predicted by Newton's theory (see also Champagne, Klopfer, & Anderson, 1980). Additionally, most people believe that heavier objects fall faster than lighter ones (Champagne et al., 1980; Shanon, 1976). Due to the presence of air resistance, there is actually a small positive relationship between the mass of a falling object and its downward acceleration (see Baurès, Benguigui, Amorim, & Siegler, 2007; Oberle, McBeath, Madigan, & Sugar, 2005); However, this positive relationship is largely overestimated by people without formal instruction in Physics (Vicovaro, 2014). For instance, when two plastic bottles of identical shape and size – one empty and one filled with water – are dropped simultaneously from just one meter high, most people believe that the filled bottle will touch the ground well sooner than the empty bottle. Actually, the two bottles will arrive to the ground almost simultaneously, meaning that their downward accelerations are nearly identical, since one meter is not enough to appreciate the effect of air resistance.[1] The belief in a strong positive relationship between mass and acceleration is persistent to change, and it is intuitively appealing not only to laypersons but also to fourth-year physics university students (Sequeira & Leite, 1991; for a comprehensive review on students' misconceptions about gravity see Kavanagh & Sneider, 2007).

* Corresponding author at: Università di Padova, Dipartimento di Psicologia Generale, via Venezia 8, I-35131 Padova, Italy.
E-mail address: michele.vicovaro@unipd.it (M. Vicovaro).

[1] The Italian Jesuit astronomer Giovanni Battista Riccioli (1598–1671) was probably the first one who measured with precision the falling speed of objects differing in mass, size, and material (Graney, 2012). In one of his experiments, two clay balls of the same size (one of which was twice as heavy as the other) were dropped simultaneously from about 85 m high. The heavier ball touched the ground 0.83 s before the lighter one. On the one hand, this confirms that the greater the mass of an object, the smaller the reduction in the downward acceleration due to the effect of air resistance, but, on the other hand, it shows that the effects of mass on downward acceleration are small, even when objects fall from great heights.

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In most of the studies in the field of the intuitive physics of gravitational motion, participants were asked to predict (i.e., to reason) about the unseen motion of a hypothetical object (e.g., Champagne et al., 1980; Sequeira & Leite, 1991; Vicovaro, 2014). By contrast, relatively little is known about people's ability to discriminate between physically plausible and physically implausible vertical falls if presented with realistic simulations of the event. Although people may fail in abstract reasoning tasks, it seems reasonable that they might have accurate knowledge of a phenomenon at a perceptual level, because the visual perception of an ongoing physical event would allow them to draw representations of physically-based, previously experienced events (Gravano, Zago, & Lacquaniti, 2017). In accordance with this hypothesis, it has been shown that judgments about physical events are more consistent with physical laws when participants are presented with virtually simulated events, as compared to when they are required to reason about abstract paper-and-pencil problems (e.g., Hecht & Bertamini, 2000; Kaiser, Proffitt, & Anderson, 1985; Kaiser, Proffitt, Whelan, & Hecht, 1992). Nevertheless, although realistic simulations of physical events may trigger stored representations of previously experienced events, this is not always the case. As studies have occasionally reported, marked discrepancies between physical laws and participants' judgments of realistic simulations of ongoing physical events can occur (e.g., Rohrer, 2003; Vicovaro, 2018; Vicovaro, Hoyet, Burigana, & O'Sullivan, 2014).

The study of subjective judgments of virtually simulated vertical fall has been limited so far by at least two technical issues. The first one is that an object that moves vertically downward on a computer screen, with approximately $1\,g = 9.81\ \text{m/s}^2$ of acceleration, remains visible for a very short time, making it difficult for the observer to evaluate the 'naturalness' of the motion. The second one concerns how the manipulation of the implied mass of the falling object actually occurs.

As to the first issue, researchers have attempted various approaches to increase the duration of the visible motion. For instance, Bozzi (1959) presented the participants with two-dimensional animations of objects descending along frictionless inclined planes, rather than presenting them with simulated vertical falls. From a physical viewpoint, a descent along a frictionless inclined plane is equivalent to a free fall, but lasts longer – on passing, this is exactly the reason why Galileo performed his experiments on an inclined plane. Bozzi (1959) found that the motion pattern that was judged as most 'natural' by participants was an accelerated one in the first third of the descent, followed by a constant velocity motion in the last two thirds of the descent. At a perceptual level, this would correspond to a constant velocity motion (see Zago & Lacquaniti, 2005). A nearly opposite pattern of results was reported by Shanon (1976), who employed edited slow-motion videos of balls falling vertically downward and found that uniformly accelerated motion was correctly judged as more natural than constant velocity motion. It is however unclear whether participants' judgements of such videos can be extended to more realistic scenarios. Twardy and Bingham (2002) presented the participants with virtual animations depicting a featureless ball falling with a parabolic trajectory from high above and that, at the end of the fall, bounced several times upon the ground. They found that animations that represented gradual *increases* in simulated gravity were on average judged as 'natural' as animations that represented Earth's gravity, whereas animations that represented gradual *decreases* in simulated gravity were judged less 'natural' than those that represented Earth's gravity. However, participants' naturalness judgments in Twardy and Bingham's (2002) study were based on the kinematic features of the bounces, rather than on the motion patterns from the beginning of the descent to the contact with the ground.

Unfortunately, the generalizability of the results of these previous studies is hindered by the fact that the involved stimuli did not represent realistic falls – as for Bozzi's (1959) and Shanon's (1976) works – or by the fact that participants' judgements were not based on the vertical fall of an object – as in the case of Twardy and Bingham's (2002). In Experiment 1 of the current study, we presented participants with wall projections of virtually simulated vertical falls, and we asked them to evaluate the 'naturalness' of each fall. The use of wall projections allowed us to maximize the duration of the simulated falls, while preserving their realism.

As to the second technical issue, i.e., the manipulation of the implied mass of the falling object, Bozzi (1959) achieved it by means of different sizes and, intriguingly, found that relatively high (low) velocities were perceived as most 'natural' for descents of large-sized (small-sized) objects.[2] Since large-sized objects are typically associated with a larger mass than smaller-sized ones, this finding might indicate a positive relationship between an object's implied mass and its perceived 'natural' velocity along an inclined plane. However, the well-known negative relationship between size and perceived velocity (Brown, 1931) implies a confounding between size and perceived velocity in Bozzi's (1959) study. Specifically, it cannot be excluded that the relatively high velocities that were judged as most 'natural' for large-sized objects were actually the same – at a perceptual level – as the relatively low velocities that were judged as most 'natural' for small-sized ones. One of the aims of Experiment 1 is to disentangle the contributions of the falling speed/acceleration and of the implied masses on the judged naturalness of the falls. We did so by varying the implied mass of the falling object through manipulations of their simulated materials, rather than through manipulations of their size.

In Experiment 1 of the current study, we presented participants with virtually simulated material objects that fell vertically to the ground from about two meters high. Participants were asked to rate the perceived naturalness of each fall. Three factors were orthogonally manipulated, namely the implied mass of the falling object (i.e., light or heavy), the motion pattern (i.e., uniform acceleration vs. uniform velocity), and the magnitude of acceleration/velocity. Hypothetically, if participants could retrieve some memory-stored representation of previously experienced phenomena, then simulated falls which are characterized by $\approx 1\,g$ acceleration should be rated as more natural than those characterized by physically implausible motions. Moreover, naturalness ratings should be largely independent of the implied mass of the simulated objects, because mass has but a small influence on the acceleration of objects falling from about two meters high.

2. Experiment 1

2.1. Participants

Thirty graduate or undergraduate students at the University of Padova participated in the experiment on a voluntary basis, and received €5 for their participation. They were aged from 20 to 34 years (M = 23.67 years, 95% CI [22.4, 25]), 18 were females and 12 were males. None of them had studied or were studying physics at the University. They had studied physics at the high school for at most three years. All participants were naive to the purpose of the experiment, and gave written informed consent according to the Declaration of Helsinki prior to their inclusion in the experiment. They all had normal or corrected-to-normal visual acuity.

2.2. Apparatus

Participants were individually seated in a dark room with their sagittal plane aligned to the vertical axis of a white vertical wall, at a distance of 340 cm (Fig. 1). Viewing was binocular; stimuli were generated with MATLAB and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and were displayed on the wall using a Canon lv7275

[2] Neither Shanon (1976) nor Twardy and Bingham (2002) manipulated the implied mass of the falling object, although the participants in Twardy and Bingham's (2002) study were verbally informed about the object's hypothetical mass.

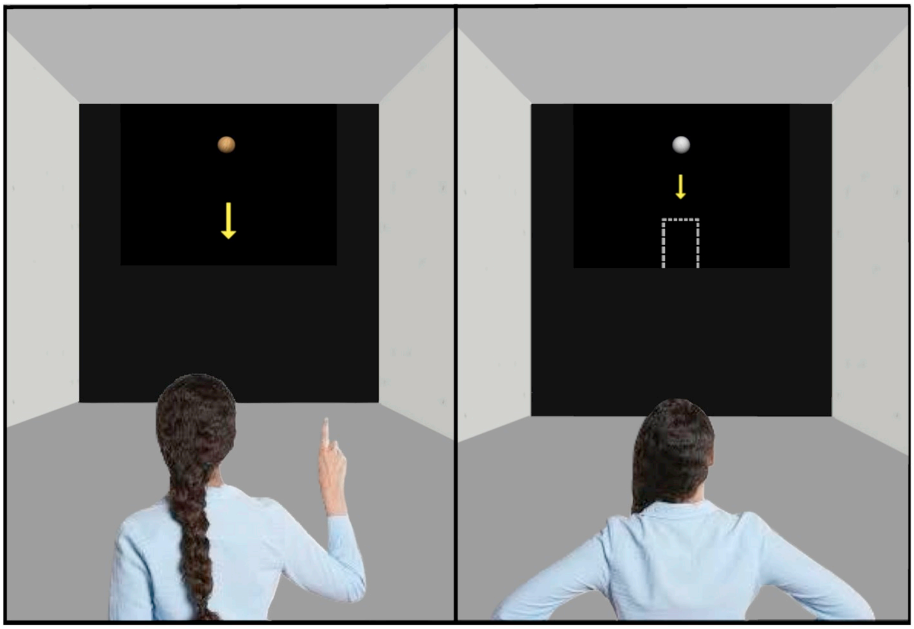

Fig. 1. A representation of the experimental setting of Experiments 1 (left) and 2 (right). For illustrative purposes, we added the arrows in order to indicate the motion direction of the simulated sphere, and we added dashed lines to indicate the invisible occluder of Experiment 2. The lights of the room were off during the experiment, therefore in the actual experimental setting the walls were dark.

projector. The size of the projected screen was 200 × 146 cm. The refresh rate was set at 60 Hz. The screen resolution was 1280 × 1024 pixels. Each pixel subtended ~1.42arcmin. Luminance measured using a Minolta LS-100 photometer ranged from 0.4 cd/m^2 to 78 cd/m^2. The background of the projected screen was black (0.4 cd/m^2 in the darkened room).

2.3. Stimuli and design

The target stimulus was a virtual projected sphere of 6.5 cm diameter, measured on the wall, subtending a visual angle of 0.54 deg. The spheres were created with 3D Studio Max. The simulated material of the sphere could be either polystyrene or wood (see Fig. 2). Photographic textures depicting the simulated materials were attached to the spheres' surfaces, and their reflectances were regulated in order to increase their realism. The luminances of the polystyrene and of the wooden spheres were respectively 78 cd/m^2 and 37 cd/m^2. At the beginning of each trial, a sphere appeared at the top of the projected screen, with its lower edge located 220 cm above the ground (136 cm above the lower margin of the projected screen). The sphere remained stationary for a duration varying randomly between 0.7 s and 1.3 s and then started falling vertically downward, until it disappeared at the end of the projected screen (84 cm - 14 deg. from the ground).

The sphere could fall either with uniform acceleration a or with uniform velocity v. In the former case, the position of the sphere as a function of time was computed according to the motion equation $S(t) = 0.5at^2$. The acceleration could attain five possible values a_i: 0.5 g, 0.9 g, 1.3 g, 1.7 g, or 2.1 g, where $g = 9.81$ m/s^2 is the approximated standard Earth's gravitational acceleration. In order to show a simulated uniformly accelerated motion, an approximate value of 0.9 g rather than 1 g was considered. Indeed, a rough estimate of the effective accelerations of real polystyrene and wooden spheres (6.5 cm diameter size and falling through air from a height of 220 cm) would be, respectively, 0.873 g and 0.988 g if the uniformly accelerated motion happened in the same time interval of the true motion (see the Appendix A for further details). The five levels a_i of acceleration were also asymmetrically distributed around 0.9 g to compensate for previous evidence that observers are less sensitive to increases than to decreases of simulated gravity (Twardy & Bingham, 2002). As for the constant velocity case, the position of the sphere as a function of time was computed using the motion equation $S(t) = vt$. Five averaged values v_{a_i} were chosen to match the corresponding levels a_i of acceleration. Average velocity $v_i = v_{a_i}(p)/2$ was obtained from the sphere's velocity $v_{a_i}(p)$ with reference to a point p located midway between the lower margin of the projected screen and the ground of the room (i.e., 178 cm below the lower edge of the sphere at initial position, and 42 cm above the ground). We thus obtained the following five levels of v: 2.07 m/s, 2.78 m/s, 3.31 m/s, 3.82 m/s, and 4.24 m/s. The matching

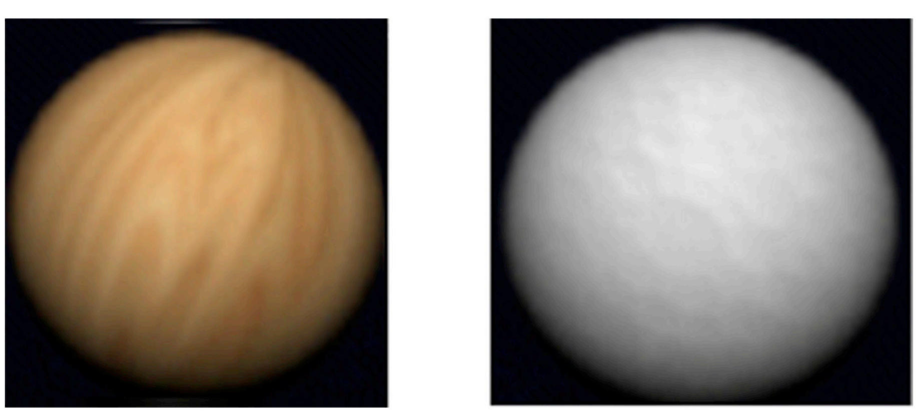

Fig. 2. A depiction of the simulated wooden (left) and polystyrene (right) spheres.

between the five levels of acceleration and velocity allowed us to conceive Motion pattern (uniform acceleration vs. constant velocity) and Magnitude (five levels) as orthogonal factors. Overall, the participants were randomly presented with 100 experimental stimuli, resulting from a 2 (Material) × 2 (Motion pattern) × 5 (Magnitude) × 5 (Replication) factorial design.

2.4. Procedure

Written instructions informed the participants that they would have been presented with a simulated sphere, made of either polystyrene or wood, which would have started falling vertically downward after few instants. Participants were asked to imagine that the sphere would have fallen as if released and not thrown downward. Participants were also informed that their task was to judge the *naturalness* of the motion, using any integer number between 0 and 100, where 0 meant completely unnatural, and 100 meant completely natural. Instructions further specified that the number 100 (0) had to be used only if the motion of the simulated sphere appeared to be utterly consistent (inconsistent) with the falling motion of a real sphere of the same size made of the corresponding material. Instructions also stressed that if the motion looked neither totally consistent nor totally inconsistent with the real one, then a number between 0 and 100 had to be used, with larger numbers for more natural motions. Before starting the experiment, participants were invited to grasp two real spheres of 6.5 cm diameter, one made of polystyrene ($m = 5$ g) and one made of wood ($m = 55$ g). The apparent size of the virtual spheres was regulated so to match that of the real spheres in order to facilitate the identification of the two. Finally, participants were first presented with ten randomly selected stimuli to familiarize with the task, and then they were randomly presented with the 100 experimental stimuli. Participants responded verbally, and their responses were recorded by an experimenter who was hidden from their sight. Naturalness (or plausibility) ratings were chosen as they are largely used in the field of intuitive physics in order to explore participants' understanding of virtually simulated physical events, and they are typically analyzed using ANOVA (e.g., Hecht & Bertamini, 2000; Sanborn, Mansinghka, & Griffiths, 2013; Schlottmann & Anderson, 1993; Twardy & Bingham, 2002; Vicovaro, 2018; Vicovaro & Burigana, 2014, 2016). Although the boundaries of the rating scale are to a certain extent arbitrary, in the present work a scale between 0 and 100 was chosen with a twofold aim: on the one hand, it provides an intuitive anchoring with the percentage of how much a motion is perceived as 'totally unnatural' and 'totally natural'; on the other hand, since the number of experimental stimuli was quite large, a large number of response alternatives should prevent, at least in principle, undesirable compression effects on the response scale (e.g., using identical numbers for stimuli that actually differ in perceived 'naturalness').

2.5. Results and discussion

Fig. 3 shows the mean naturalness ratings averaged across both participants and replications. We performed a three-way within-participants ANOVA on the naturalness ratings with the factors *Material*, *Motion pattern*, and *Magnitude*. Naturalness ratings were strongly affected by the material × magnitude interaction ($F(4,116) = 28.27$, $p < .001$, $\eta_G^2 = 0.17$). Specifically, the mean naturalness ratings for the simulated wooden sphere increased sharply moving from the first to the second level of the magnitude factor, and then exhibited little variation across the other levels of the factor. A nearly opposite pattern emerged for the simulated polystyrene sphere, as the mean naturalness ratings decreased with the magnitude factor.[3] The ANOVA also

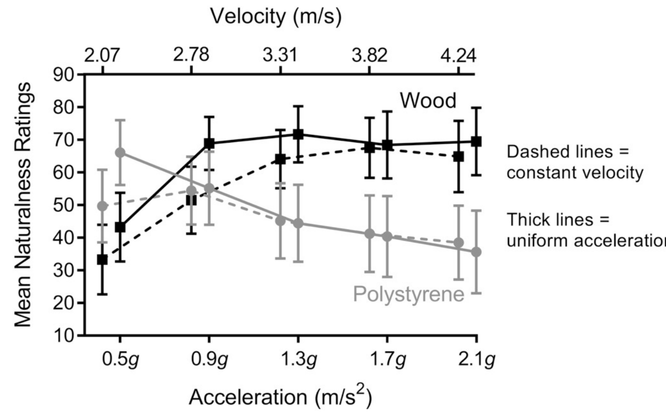

Fig. 3. The mean naturalness ratings from Experiment 1. The vertical bars represent 95% confidence intervals. The thick lines are for uniformly accelerated motion, whereas the dashed lines are for constant velocity motion. Colour grey is used for the polystyrene simulated sphere, whereas colour black is used for the simulated wooden sphere. The five levels of uniform acceleration are represented on the bottom horizontal axis, and the corresponding five levels of constant velocity are represented on the top horizontal axis.

revealed a main effect of the motion pattern factor ($F(1,29) = 11.03$, $p < .005$, $\eta_G^2 = 0.016$). Overall, the naturalness ratings for the uniformly accelerated motion, averaged across both participants and factors material and magnitude, were larger than the naturalness ratings for the constant velocity motion ($M = 56.35$, 95% CI [52, 60.7]; $M = 51.05$, 95% CI [46.5, 55.6], respectively). This main effect was qualified by a statistically significant motion pattern × magnitude interaction ($F(4,116) = 7.8$, $p < .005$, $\eta_G^2 = 0.015$) and also by a statistically significant three-way interaction ($F(4,116) = 7.57$, $p < .001$, $\eta_G^2 = 0.008$). The latter interaction suggests that, especially for the wooden simulated sphere, naturalness ratings were larger for the uniformly accelerated motion than for the constant velocity one, but only at the lowest levels of the magnitude factor (see Fig. 3). As for the main effects of factor material, they were statistically significant ($F(1,29) = 23.03$, $p < .001$, $\eta_G^2 = 0.095$), whereas the main effects of factor magnitude were not ($F(4,116) = 1.68$, $p = .16$, $\eta_G^2 = 0.026$). Finally, the material × motion pattern interaction was not statistically significant ($F(1,29) = 2.17$, $p = .15$, $\eta_G^2 = 0.004$).

A close inspection of the data showed a negative correlation between the mean naturalness ratings and their variance ($r = -0.71$, $t(18) = -4.25$, $p < .001$). This suggests that participants used a restricted range of numbers for the more 'natural' motions (e.g., 70–80), whereas for the 'unnatural' ones some participants used the lower end of the rating scale (e.g., 5–10), while others the middle part of the scale (e.g., 40–50). The latter result indicates that the concept of 'unnatural motion' is somewhat arbitrary, a point which is worthy of being explored in future studies. For the purpose of the present study, it was important to verify that the outcomes of Experiment 1 were not a by-product of the violation of ANOVA assumptions. In this regard, we first note that the statistical significance of the main and interaction effects did not change after the application of the correction methods for the violation of the sphericity assumption.[4] Moreover, a *quadratic* transformation of the participants' responses was performed (i.e., $R_T = R^2$, where R_T is the transformed response and R is the original response),

[3] Visual inspection of the graphs for each participant data showed that the material × magnitude crossover interaction represented in Figure 3 emerged at

(*footnote continued*)
the individual level for 17 out of 30 participants. The same interaction, observed at the group level, is thus not a by-product of averaging the naturalness ratings across participants.

[4] Although Mauchly's Test showed violations of sphericity for the main effects of the magnitude factor, as well as for all the interaction effects involving magnitude, the application of the Greenhouse-Geisser and of the Huynd-Feldt corrections left the significance levels unchanged.

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which allowed to eliminate the mean-variance correlation ($r = 0.09$, $t(18) = 0.39$, $p = .70$).[5] The results of the ANOVA on the transformed data closely mirror those of the ANOVA on the untransformed data, which supports the reliability of the results of Experiment 1.[6]

In order to evaluate the degree of consistency of participants' naturalness ratings with the physics of vertical fall, the ratings for the 0.9 *g* motion were compared (separately for the two simulated materials) with those of all the other combinations of factors motion pattern and magnitude. Specifically, separate paired-sample *t*-tests were computed, after which Hochberg's (1988) sequentially acceptive step-up Bonferroni procedure was applied in order to identify statistically significant comparisons (see also Keselman, 1994). The results of the 18 *t*-test (i.e., nine tests for each simulated material) are reported in Table 1, in decreasing order of *p*-value. The *p*-values of statistically significant comparisons (according to Hochberg's (1988) criterion) are highlighted in bold typeface. For the polystyrene sphere, the physically plausible 0.9 *g* motion was not rated as significantly more natural than the 0.5 *g* motion and the 2.07 m/s and 2.78 m/s constant velocity motions, whereas all the other comparisons were statistically significant. The opposite pattern of results emerged for the simulated wooden sphere. Overall, the results showed that, especially for the simulated wooden sphere, the naturalness ratings for the physically plausible 0.9 *g* motion did not significantly differ from the naturalness ratings for several of the other combinations of the motion pattern and magnitude factors.

Thus, the results of Experiment 1 do *not* provide support to the hypothesis that participants could draw representations of physically-based, previously experienced vertical falls. The findings appear instead to reflect some biased knowledge of vertical fall. Specifically, these results are consistent with the idea that participants used a ‘heavy-fast, light-slow’ heuristic, which would explain why relatively low values of acceleration/velocity were judged to be natural for the simulated polystyrene sphere, whereas relatively high values of acceleration/velocity were judged to be natural for the simulated wooden sphere. Moreover, results failed to reveal a clear preference for uniformly accelerated motion over constant velocity motion, as if participants focused on the relationship between the magnitude and the material factors, while giving relatively little importance to the actual motion pattern. With respect to this latter finding, it is worth emphasizing two points. The first one is that when an object starts moving from rest with constant velocity (as in the case of the constant velocity motion pattern of Experiment 1), an illusory acceleration is usually perceived at the beginning of the motion, while in the remaining part of the trajectory the object is perceived to move at a constant velocity (Runeson, 1974). The second point is that it is unlikely that the small contribution of the motion pattern factor to the naturalness ratings could be due to a participants' failure in perceiving a difference between constant velocity and uniformly accelerated motions. Previous studies showed that, for an object that moves from point *A* to point *B*, acceleration is detected when the object's velocity at point *B* is at least 25% larger than the object's velocity at point *A* (Brower, Brenner, & Smeets, 2002; see also Werkhoven, Snippe, & Toet, 1992). For all the five levels of uniform acceleration of Experiment 1, the object's velocity at the end of its visible trajectory (i.e., the end of the projected screen) was about 41% larger than the velocity at the midpoint of the visible trajectory. This suggests that, for the uniformly accelerated motion, the target was perceived as accelerating until the end of its visible trajectory, and not just at the beginning as it would occur in a constant velocity motion. Therefore, the most likely explanation for the lack of a clear effect of the motion pattern factor on the judged naturalness of simulated falls, is that participants actually focused on a ‘heavy-fast, light-slow’ heuristic, and not that they did not perceive the difference between constant velocity and uniformly accelerated motion.

As a final note, it is worth emphasizing that assuming a uniform ≈0.9 *g* acceleration as the physically correct motion, for both the polystyrene and wooden spheres, is an approximation. The actual motion has a variable acceleration that decreases with time (see the discussion in the Appendix A for further details). This time-dependent decrease of acceleration would be larger for the polystyrene than for the wooden sphere. Nonetheless, such an approximation is in line with previous studies in which a uniformly accelerated motion has been typically considered as an adequate approximation of the ‘physically correct’ gravitational motion (e.g., Shanon, 1976; Twardy & Bingham, 2002; Zago & Lacquaniti, 2005). In addition, since results show that a large difference in the motion pattern, such as that implied by constant velocity and uniform acceleration, actually produced small effects on the naturalness ratings, it is reasonable to speculate that a subtle difference like that between uniform acceleration and decreasing acceleration would have had a very small impact on the results. Nevertheless, it is a topic worth of further considerations and experiments.

3. Experiment 2

Results of Experiment 1 suggest that judgments of the perceived naturalness of vertical falls were likely driven by a ‘heavy-fast, light-slow’ heuristic, rather than by representations of physically-based, previously experienced vertical falls. A possible interpretation of this finding is that instructions to judge the ‘naturalness’ of the motion may have led the participants to reason about the meaning of ‘natural’ or ‘physically plausible’ motion in the case of vertical fall. This may have activated participants' biased (i.e., heuristic) knowledge of the phenomenon, preventing them from relying on stored representations of previously experienced vertical falls. Since Experiment 2 aimed at exploring the intuitive physics of vertical fall at a more *implicit* level, by means of a prediction-motion (PM) task, the use of such a heuristic by participants is expected to be minimized. In a typical PM task, participants are presented with a target moving horizontally and then disappearing behind a visible or invisible occluder. Their task is to indicate (e.g., by pressing a key) when the target would arrive at a given point of interception (e.g., the end of the occluder; for reviews on PM tasks see Makin, in press; Tresilian, 1995). In this type of task, the time-to-contact (TTC) is defined as the time between the disappearance of a target's leading edge behind the occluder, and when it would make contact with a given point of interception. The difference between the ‘total response time’ (total response time = TTC + duration of the visible trajectory) and the ‘physical arrival time’ results in the ‘constant error’.

Differently from the perceptual judgment task of Experiment 1, in PM tasks participants are not explicitly required to evaluate naturalness of the motion. Use of PM tasks should therefore minimize the probability that participants may base their responses on a biased knowledge of physical events, and it should instead maximize the likelihood that participants rely on stored representations of physically-based, previously experienced events. For instance, Huber and Krist (2004) presented participants with simulations of a ball rolling towards the edge of a horizontal elevated surface. An opaque rectangle was added next to the edge of the surface, in order to occlude the motion of the ball after it fell off the surface. Participants in one group were asked to

[5] An arcsin transformation was also applied to the participants' responses ($R_T = 2\arcsin(\sqrt{R/100})$), since this transformation is often used for de-correlating means and variances in the case of bounded data (see Winer, Brown, & Michels, 1991, p. 356). However, after such transformation data still showed a strong mean-variance correlation ($r = -0.68$, $t(18) = -3.97$, $p < .001$).

[6] For the transformed data we obtained statistically significant main effects of the motion pattern factor ($F(1,29) = 14.34$, $p < .001$, $\eta_G^2 = 0.017$) and of material factor ($F(1,29) = 24.\ 3$, $p < .001$, $\eta_G^2 = 0.06$), whereas the main effects of factor magnitude were not significant ($F(4,116) = 1.29$, $p = .28$, $\eta_G^2 = 0.016$). The material × magnitude interaction was significant ($F(4,116) = 23.11$, $p < .001$, $\eta_G^2 = 0.12$), as well as the motion pattern × magnitude interaction ($F(4,116) = 3.4$, $p < .05$, $\eta_G^2 = 0.006$) and the three-way interaction ($F(4,116) = 6.39$, $p < .001$, $\eta_G^2 = 0.007$). The material × motion pattern interaction was not statistically significant ($F(1,29) = 1.32$, $p = .26$, $\eta_G^2 = 0.002$).

Table 1
The results of paired-sample *t*-tests comparing the naturalness ratings for the physically plausible 0.9 *g* motion with the naturalness ratings for the other combinations of magnitude and motion pattern, separately for polystyrene (left) and wood (right). Statistically significant results are highlighted in bold typeface.

Polystyrene

0.9*g* vs.	t(29) =	*p* =
2.78m/s	0.179	.86
2.07m/s	0.805	.43
0.5*g*	-1.886	.069
3.31m/s	2.750	**.01**
1.3*g*	3.045	**.005**
1.7*g*	3.210	**.0032**
3.82m/s	3.262	**.0029**
4.24m/s	3.597	**.0012**
2.1*g*	3.902	**.0005**

Wood

0.9*g* vs.	t(29) =	*p* =
1.7*g*	0.085368	.93
2.1*g*	-0.10118	.92
3.82m/s	0.26252	.80
4.24m/s	0.63845	.53
1.3*g*	-0.73951	.47
3.31m/s	1.1254	.27
2.78m/s	3.4838	**.0016**
0.5*g*	6.7242	**2.32×10^{-7}**
2.07m/s	6.9372	**1.26×10^{-7}**

imagine the falling motion of the ball, and to predict the TTC using a rating scale. Participants in another group were asked to imagine the falling motion of the ball, and to estimate the TTC of the ball by pressing a mouse button when they thought that the ball had just arrived to the ground (i.e., a PM task). Results showed that participants' responses were more consistent with the physics of parabolic motion in the PM task than in the rating task. This suggests that, differently from the rating task, the PM task could activate physically-based representations of parabolic motion (see also Bosco, Delle Monache, & Lacquaniti, 2012).

As to vertical fall, Zago, Iosa, Maffei, and Lacquaniti (2010) presented participants with large-size animations showing a square that fell vertically downward from about two meters high with a given initial velocity, and then disappeared behind an invisible occluder. The target remained occluded for a relatively short time, ranging from 75 to 271 msec. Participants were asked to press a mouse button when the target would arrive at a visible point of interception located below the point of target's disappearance. Prior to disappearance, the target could move with physically-based uniform acceleration (1 *g*), with constant velocity (0 *g*), or with uniform deceleration (−1 *g*). Results showed that participants' responses were substantially accurate in the case of 1 *g* motion, whereas underestimations of the TTC of the target emerged for the 0 *g* and -1 *g* motions. A plausible interpretation of these results is that participants implicitly expected the target to move with uniform 1 *g* acceleration during the invisible part of its trajectory, which provides support to the hypothesis that participants' performance in this PM task was driven by an internalized model of gravity (see McIntyre, Zago, Berthoz, & Lacquaniti, 2001).

The results obtained by Zago et al. (2010) suggest that internal representations of vertical fall – as revealed by PM tasks – might be substantially more accurate than participants' responses in abstract reasoning or naturalness ratings tasks. In Experiment 2, we presented the participants with the same stimuli of Experiment 1, except that at some point of the descent the simulated sphere disappeared behind an invisible occluder. The task of the participants was to press a key when they thought that the sphere had just touched the floor of the room (see Fig. 1). If participants possessed an internalized model of gravity, they should implicitly expect the target to move with uniform ≈1 *g* acceleration during the occluded part of its trajectory. Thus the following patterns should be observed: Firstly, estimated TTC should be substantially accurate for a 0.9 *g* acceleration; Secondly, TTC should be underestimated (overestimated) when the physical arrival time is larger (smaller) than the one implied by a uniform ≈1 *g* acceleration. That is, it should be underestimated in the cases of 0.5 *g* acceleration and of 2.07 m/s constant velocity, and overestimated in the cases of 1.3 *g*, 1.7 *g*, 2.1 *g* accelerations and of 3.31 m/s, 3.82 m/s, 4.24 m/s constant velocities. In sum, if participants implicitly expected the target to move with uniform ≈1 *g* acceleration during the occluded part of its trajectory, then constant error (total response time - physical arrival time) should increase with the magnitude factor.

A relevant feature of the PM task of Experiment 2 is that, by employing simulated wooden and polystyrene spheres, it was possible to investigate the influence of the target's implied mass on TTC estimations – a topic that has remained largely unexplored in literature on PM tasks due to the use of targets characterized by featureless two-dimensional shapes. If the estimated TTC for a simulated wooden sphere were smaller than that of a simulated polystyrene sphere, this would support the hypothesis that participants' implicit or explicit knowledge of the relationship between an object's mass and its falling speed might affect TTC estimations. Indeed, Tresilian (1995) highlighted the possible influence of cognitive factors on TTC estimation. In addition, the results obtained by Makin, Stewart, and Poliakoff (2009) provide further support to the hypothesis that participants' knowledge of the 'typical' velocity of a target may affect the target's estimated TTC.

3.1. Participants

Participants were the same as those of Experiment 1. The order of the experiments was counterbalanced across participants.

3.2. Apparatus

The apparatus was the same as in Experiment 1.

3.3. Stimuli and design

The experimental setting was the same as in Experiment 1, except that the simulated sphere disappeared behind an invisible rectangle occluder at some point of its trajectory. The occluder covered the last 98.5 cm (16.48 deg) or the last 170.5 cm (28.15 deg) of the sphere's trajectory from the starting point of the descent to the floor of the room, corresponding to 44.8% and 77.5% of the trajectory, respectively. The participants were randomly presented with 200 experimental stimuli, resulting from a 2 (Material) × 2 (Motion pattern) × 2 (Occluder length) × 5 (Magnitude) × 5 (Replication) factorial design. For the uniformly accelerated motion, the physical arrival times for the five levels of the magnitude factor were respectively 946, 705, 586, 513, and 462 msec, whereas for the constant velocity motion, the physical

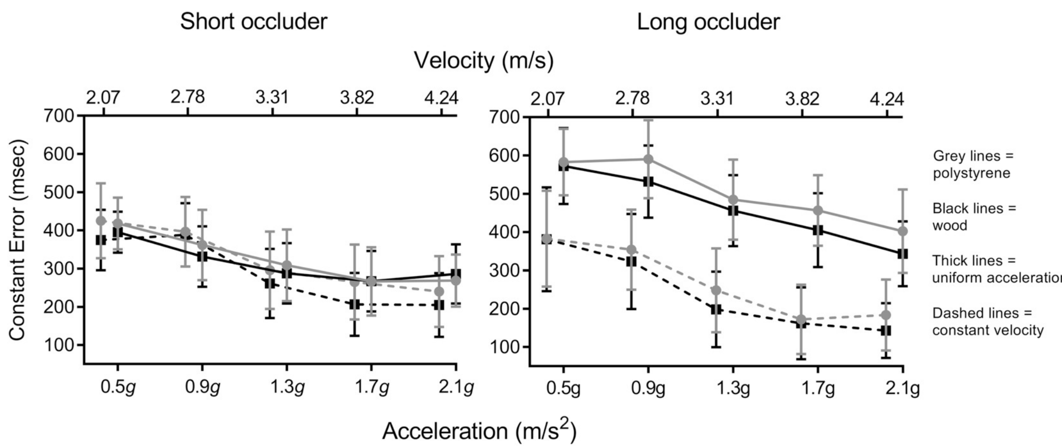

Fig. 4. The mean constant error (total response time – physical arrival time) from Experiment 2 for the short occluder (left panel) and for the long occluder (right panel). The vertical bars represent the 95% confidence intervals. The thick lines are for uniformly accelerated motion, whereas the dashed lines are for constant velocity motion. Colour grey is used for the polystyrene simulated sphere, whereas colour black is used for the simulated wooden sphere. The five levels of uniform acceleration are represented on the bottom horizontal axis, and the corresponding five levels of constant velocity are represented on the top horizontal axis.

arrival times were respectively 1059, 789, 663, 575, and 517 msec. The duration of the visible part of the trajectory and that of the TTC varied across combinations of levels of factors motion pattern, occluder length, and magnitude. The TTC ranged from 216 msec (uniformly accelerated 2.1 *g* motion, short occluder) to 824 msec (constant velocity 2.07 m/s motion, long occluder).

3.4. Procedure

The written instructions were the same as those in Experiment 1, except that the participants were told that, at some point of the descent, the sphere would have passed behind an invisible occluder, and that their task was to judge the *time to contact* between the lower edge of the sphere and the floor of the room. They were instructed to press "SPACE" on a PS/2 BenQ i100 keyboard at the exact time of impact of the lower edge of the sphere with the floor of the room (see also Note 9). The keyboard was leaning on the participants' knees. Apart from this, the experimental procedure was the same as in Experiment 1.

3.5. Results and discussion

Fig. 4 shows the constant error (CE), that is, the difference between the 'total response time' (estimated TTC + duration of the visible trajectory) and the 'physical arrival time', averaged across both participants and replications. Positive CEs suggest that total response times were consistently higher than the corresponding physical arrival times, meaning that participants systematically overestimate the TTC of the simulated sphere with the floor of the room. In Fig. 5 we represent the estimated TTC (total response time– duration of the visible trajectory), averaged across both participants and replications. We performed a four-way within-participants ANOVA on CE with the factors *Material*, *Motion pattern*, *Occluder length* and *Magnitude*.[7] All main effects were statistically significant: $F(1,29) = 18.09, p < .001, \eta_G^2 = 0.013$ for the material factor, $F(1,29) = 64.13, p < .001, \eta_G^2 = 0.178$ for the motion pattern factor, $F(1,29) = 11.46, p < .005, \eta_G^2 = 0.045$ for the occluder length factor, and $F(4,116) = 38.75$, $p < .001$, $\eta_G^2 = 0.240$ for the magnitude factor. Except for a small three-way material × motion pattern × occluder length interaction ($F(1,29) = 4.88$, $p = .035$, $\eta_G^2 = 0.002$), none of the interactions involving the material factor were statistically significant. Indeed, we obtained $F(1,29) = 0.61$, $p = .44$, $\eta_G^2 = 0.0001$ for the material × motion pattern interaction, $F(1,29) = 0.73$, $p = .40$, $\eta_G^2 = 0.0003$ for the material × occluder length interaction, $F(4,116) = 0.15$, $p = .96$, $\eta_G^2 = 0.0002$ for the material × magnitude interaction, $F(4,116) = 0.98$, $p = .42$, $\eta_G^2 = 0.002$ for the material × occluder length × magnitude interaction, $F(4,116) = 0.37$, $p = .83$, $\eta_G^2 = 0.001$ for the material × motion pattern × magnitude interaction, and $F(4,116) = 0.86$, $p = .49$, $\eta_G^2 = 0.001$ for the four-way interaction. There was a strong motion pattern × occluder length interaction ($F(1,29) = 228.7$, $p < .001$, $\eta_G^2 = 0.146$), and a relatively small occluder length × magnitude interaction ($F(4,116) = 3.02$, $p = .02$, $\eta_G^2 = 0.007$). Neither the motion pattern × magnitude interaction nor the occluder length × motion pattern × magnitude interaction were significant ($F(4,116) = 2.36$, $p = .057$, $\eta_G^2 = 0.007$, and $F(4,116) = 2.14$, $p = .08$, $\eta_G^2 = 0.006$, respectively). Lastly, Mauchly's Test showed that the sphericity assumption was violated for the main effects of the magnitude factor and for the effects of the motion pattern × magnitude interaction, but the application of the Greenhouse-Geisser and of the Huyn-Feldt corrections had no consequences on the significance levels.

The main results of Experiment 2 can be summarized as follows. 1) For all combinations of the four experimental factors, participants systematically overestimated the target's TTC. 2) The estimated TTC for the simulated wooden sphere was slightly but consistently smaller than the estimated TTC for the simulated polystyrene sphere. On average, the estimated TTC for the simulated wooden sphere was 29.3 msec smaller than the estimated TTC for the simulated polystyrene sphere (95% CI[15.8 msec, 42.8 msec]).[8] This finding shows that, for targets

[7] The objective (i.e., physical) influence of factors magnitude, occluder length, and motion pattern on the physical arrival time (duration of the visible trajectory + TTC) is 'factored out' from the CE, because CE results from the difference between estimated and physical arrival times. Therefore, an analysis on CE allows us to explore the effects of the experimental factors on the estimated TTC, independently of their effects on the physical TTC. By contrast, the estimated TTC will largely reflect the objective influence of the three experimental factors (material is excluded) on the physical TTC. Specifically, the physical TTC decreases with the magnitude factor, it is longer for the long than for the short occluder, and it is longer for constant velocity than for uniform acceleration.

[8] A standard keyboard has a polling rate of 125 Hz but the random error can be quite large (e.g., about 30 msec). On each trial, the estimated CE corresponds to the sum of the actual CE and of such random error *e*, where the latter can be conceived as a normally distributed variable with unknown mean μ_e and unknown variance σ_e^2. As regards the impact of this random error on the small 29.3 msec difference between the CEs for the two simulated spheres, we note that, by subtracting the mean CEs for the simulated wooden and polystyrene spheres, we also subtracted the corresponding mean random errors, whose difference is normally distributed with mean 0. Therefore, the keyboard mean

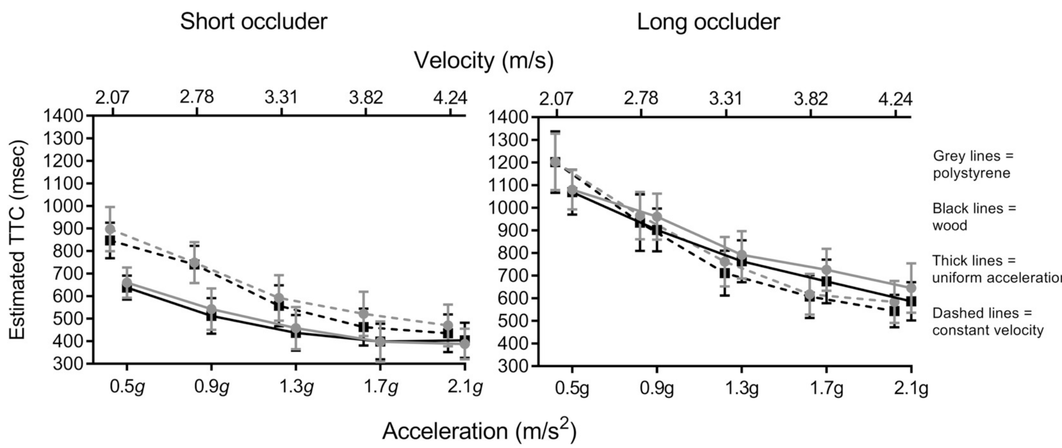

Fig. 5. The mean estimated TTC from Experiment 2 for the short occluder (left panel) and for the long occluder (right panel). The vertical bars represent the 95% confidence intervals. The thick lines are for uniformly accelerated motion, whereas the dashed lines are for constant velocity motion. Colour grey is used for the polystyrene simulated sphere, whereas colour black is used for the simulated wooden sphere. The five levels of uniform acceleration are represented on the bottom horizontal axis, and the corresponding five levels of constant velocity are represented on the top horizontal axis.

moving vertically downward, the target's implied mass may affect TTC estimates in a PM task. 3) CE decreased with the magnitude factor. Note that if percentage rather than absolute constant error were represented on the vertical axis, then the lines in Fig. 4 would be approximately flat, rather than negatively inclined. In other words, percentage overestimation of the TTC remained approximately constant with the magnitude factor. 4) As shown by the strong motion pattern × occluder length interaction, the effect of the occluder length factor on estimated TTC was mediated by the motion pattern factor. Specifically, for the constant velocity motion, the mean CE for the long occluder, averaged across participants and across factors material and magnitude was slightly smaller than the mean CE for the short occluder ($M = 254.8$ msec, 95% CI [166 msec, 344 msec] and $M = 305.7$ msec, 95% CI [228 msec, 383 msec], respectively; $t(29) = 2.63$, $p = .01$, $d_z = 0.48$). By contrast, the opposite pattern of results emerged for the uniformly accelerated motion, as the mean CE for the long occluder ($M = 482.5$ msec, 95% CI [399 msec, 566 msec]) was clearly larger than the mean CE for the short occluder ($M = 319.1$ msec, 95% CI [251 msec, 387 msec]; $t(29) = 9.76$, $p < .001$, $d_z = 1.78$).[9]

Interestingly, none of the main outcomes of Experiment 2 is consistent with the hypothesis that participants' responses were driven by physically-based representations of vertical fall (i.e., by an internalized model of gravity). In particular, CE decreased with the magnitude factor, which is the opposite of what it should have been observed if participants implicitly expected the target to move with uniform ≈1 *g* acceleration during occlusion. The results of Experiment 2 appear instead to be consistent with those obtained in various studies that employed PM tasks with targets moving in a horizontal direction, which have reported a systematic overestimation of the TTC mostly (but not exclusively) for actual TTCs shorter than 1 s (Battaglini, Campana, & Casco, 2013; Benguigui & Bennett, 2010; Benguigui, Ripoll, & Broderick, 2003; Bennett & Benguigui, 2013; Jagacinski, Johnson, & Miller, 1983; Peterken, Brown, & Bowman, 1991; Rosenbaum, 1975; Yakimoff, Mateeff, Ehrenstein, & Hohnsbein, 1993). For the constant velocity motion, the CE was slightly larger for the shorter than for the longer occluder. This result is somewhat inconsistent with the reported positive relationship between CE and occlusion duration (e.g. Jagacinski et al., 1983; Rosenbaum, 1975; Yakimoff et al., 1993), but it is in line with the results reported by Runeson (1975), who also employed targets that started moving from a static position with constant velocity. We recall that a target that starts moving from a static position with constant velocity is perceived to accelerate at the beginning of its motion (see Runeson, 1974). Consistently with Runeson's (1975) interpretation of the results of his own study, we hypothesize that, only in the case of the long occluder, the target was still perceived to accelerate when it disappeared behind the occluder, so that participants may have extended this illusory acceleration to the whole occluded motion. This would indeed result in the observed smaller estimated TTC for the longer occluder. Results of Experiment 2 also showed that, for the uniformly accelerated motion, estimated TTC was larger for the long than for the short occluder. This is consistent with the results obtained in previous PM studies that employed a uniformly accelerated target moving in a horizontal direction (Benguigui et al., 2003; Bootsma & Oudejans, 1993; Jagacinski et al., 1983; Rosenbaum, 1975; Runeson, 1975). The large overestimation of the TTC for the uniformly accelerated motion with the long occluder probably reflects the participants' difficulty to extrapolate the correct acceleration of targets when only a small part of target's trajectory is visible (e.g., Jagacinski et al., 1983).

An important outcome of Experiment 2 is that TTC estimates decreased with the implied mass of the target, as if participants expected the simulated wooden sphere to move slightly faster than the simulated polystyrene sphere in the occluded part of the trajectory. This outcome, as well as the other main outcomes of Experiment 2, does not appear to depend on the order in which participants took part in the experiments. Indeed, a five-way mixed ANOVA carried on CE, with *Order* as a between-subject factor and *Material*, *Motion pattern*, *Occluder length* and *Magnitude* as within-subject factors, showed that neither the main effect nor the interactions involving the order factor were statistically significant, except for a difficult to interpret order × material × motion pattern × magnitude interaction ($F(4,112) = 3.9$, $p < .01$, $\eta_G^2 = 0.003$). Most importantly, the effects of the order × material

(*footnote continued*)
random error affecting the mean 29.3 msec difference between the CEs for the two simulated spheres should be approximately equal to 0. Nevertheless, random error might have had a non-negligible impact on the variability of the estimated CE measures, which would imply that the actual η_G^2 values for the main and interaction effects of the factors that we manipulated in Experiment 2 could be slightly larger than those reported above.

[9] Individual data reflect quite closely the main features of group data visible in Fig. 4. 1) All 30 participants overestimated the TTC. 2) For 21 participants, the estimated TTC for the simulated wooden sphere was smaller than the one of the simulated polystyrene sphere. 3) For 26 participants, the CE decreased with the magnitude factor. 4) For 22 participants, the mean CE for the long occluder was smaller than the mean CE for the short occluder in the constant velocity motion, whereas for the uniformly accelerated motion the opposite held for all participants.

interaction were small and not significant ($F(1,28) = 0.51$, $p = .48$, $\eta_G^2 = 0.0001$), a result that contributes to rule out the hypothesis that the effects of the target's implied mass on estimated TTC could be an artefact due to the order of the experiments.[10]

4. General discussion

People without formal instruction in Physics tend to explicitly believe that heavier objects fall faster than lighter ones (Champagne et al., 1980; Sequeira & Leite, 1991; Shanon, 1976; Vicovaro, 2014). Contrary to what could be expected on the base of previous studies that compared explicit and perceptual judgements of physical events (Hecht & Bertamini, 2000; Kaiser et al., 1985; Kaiser et al., 1992), results of Experiment 1 showed that participants responded according to a ‘heavy-fast, light-slow’ heuristic, even when presented with ongoing simulated vertical falls. A result that implies that they could *not* draw representations of physically-based, previously experienced vertical falls. A similar conclusion has recently been reached by Gravano et al. (2017) in a study on imagined, rather than visually perceived vertical fall. Moreover, the results of Experiment 1 are in line with the results of previous studies that showed marked discrepancies between the predictions from physical laws and participants' judgments of realistic simulations of ongoing physical events (e.g., Rohrer, 2003; Vicovaro, 2018; Vicovaro et al., 2014).

Physics teachers may have a hard time trying to modify students' idea that heavier objects fall much faster than lighter ones (see Kavanagh & Sneider, 2007; Sequeira & Leite, 1991). Although experts in Physics may dismiss this idea as a trivial mistake due to scarce knowledge of Newtonian mechanics, it is interesting to note that even brilliant minds such as Aristotle and Medieval scholars were firmly convinced that the mass of objects has a strong effect on their falling speed (e.g., Darling, 2006). The results of Experiment 1 highlight the pervasiveness of the ‘heavy-fast, light-slow’ heuristic, as it appears to affect not only the explicit but also the perceptual judgements of vertical falls. Understanding the origins of this heuristic would be important not only to shed light on the processes that stand at the basis of our representations of the physical world, but also to implement more effective strategies for the teaching of Physics. Unfortunately, a clear explanation of the heuristic is still lacking, although some researchers have speculated that it might originate from perceptual-motor experience with physical objects (Rohrer, 2003; Vicovaro, 2014). The rationale underlying this hypothesis starts from the observation that a heavy object tends to exert a greater downward force than a light object. Because a force in a given direction is usually a good predictor of a velocity or an acceleration in the same direction, people may intuitively believe that an object that exerts a greater downward force than another object would also fall to the ground faster. This tentative explanation of the origins of the ‘heavy-fast, light-slow’ heuristic relates to the general principle of ‘externalization of body dynamics’, which has been proposed as a possible explanation of the misconceptions about projectiles motion (Hecht & Bertamini, 2000).

The results of Experiment 2 showed that the target's implied mass affected TTC estimations in a PM task, with smaller TTC estimations for the simulated wooden sphere than for the simulated polystyrene sphere (average difference = 29.3 msec, 95% CI[15.8 msec, 42.8 msec]). This finding appears to be related to the results obtained by Kozhevnikov and Hegarty (2001), who showed that the remembered vanishing position of targets with a large implied mass was slightly displaced in the direction of gravity as compared to that of targets with a small implied mass. Although the PM task of Experiment 2 was meant to minimize the probability that participants could base their responses on a biased knowledge of vertical fall, a plausible explanation of the effects of implied mass on estimated TTC is that the ‘heavy-fast, light-slow’ heuristic affected the TTC estimations. This hypothesis would be consistent with the idea that TTC estimations can be affected by cognitive factors, like participants' beliefs about the ‘typical’ velocity of a target (see Makin et al., 2009; Tresilian, 1995). A possible alternative explanation of the results is that the influence of the target's implied mass on participants' responses in Experiments 2 reflects an implicit, automatic association between mass and falling speed, in line with what it was suggested by Kozhevnikov and Hegarty (2001). In this regard, it is worth noting that, as it is showed in the Appendix A, due to the effects of air resistance a real 6.5 cm diameter wooden sphere falling from a height of 220 cm would actually touch the ground 43 msec earlier than a 6.5 cm diameter polystyrene falling from the same height. A single-sample *t*-test showed that the 29.3 msec difference between the mean estimated CEs for the polystyrene and wooden spheres was not significantly different from 43 msec ($t(29) = -1.99$, $p = .056$, $d_z = 0.36$). This suggests that an implicit association between mass and falling speed that leads to slightly smaller TTCs for heavier than for lighter objects, and of a comparable size with respect to the actual physical difference, may allow participants to comply with the actual behaviour of real objects that fall in air, thus increasing the accuracy of their responses.

The similarity between the pattern of results that we obtained in the PM task of Experiment 2, and the pattern of results that is typically obtained in PM tasks in which the target moves in a horizontal direction, suggests that comparable cognitive and perceptual process may underlie participants' responses in the two situations. Models of TTC estimation in PM tasks can be broadly divided into two categories, depending on whether they emphasize the role of people's sensitivity to optical information that specifies TTC (e.g., Benguigui et al., 2003; Benguigui & Bennett, 2010; Bootsma & Oudejans, 1993), or whether they emphasize the role of visuo-spatial attention (e.g., Bennett & Benguigui, 2013; de'Sperati & Deubel, 2006; Jonikaitis, Deubel, & de'Sperati, 2009; Lyon & Waag, 1995; Makin & Poliakoff, 2011). Experiment 2, however, was not designed to test the contribution of optical variables and visuo-spatial attention to TTC estimation, indeed both types of models can account for most of the results of Experiment 2. For instance, the large TTC overestimations obtained for uniformly accelerated targets with the long occluder can either be explained in terms of participants' sensitivity to first-order perceptual information (see Benguigui et al., 2003; Bootsma & Oudejans, 1993), or in terms of the difficulty to extrapolate the motion of accelerated targets (see Jagacinski et al., 1983). It may also be the case that the lack of sensitivity to optical acceleration had an effect on motion extrapolation, implying that the observed results are related to both perceptual and attentional processes. However, neither the sensitivity to optical information that specifies TTC, nor attentional processes appear to be able to explain, in a relatively straightforward manner, the influence of the target's implied mass on estimated TTC. The results of Experiment 2 are difficult to explain without assuming that people's heuristic beliefs about the motion of objects, or an implicit association between mass and falling speed, may affect TTC estimation in a PM task.

According to the ‘1 *g* model’, interceptive actions of objects that fall vertically downward would be driven by accurate implicit, action-oriented knowledge of gravity (McIntyre et al., 2001; Zago, McIntyre, Senot, & Lacquaniti, 2008; cf. Baurès et al., 2007). Support to the 1 *g* model comes from two main observations: Firstly, despite poor explicit knowledge of vertical fall, people have good *action-oriented* knowledge of the phenomenon, as they can usually intercept objects that fall

[10] Similarly, the outcomes of Experiment 1 were largely independent of the *Order* factor. A four-way mixed ANOVA in naturalness ratings with *Order* as a between-subject factor and *Material*, *Motion pattern*, and *Magnitude* as within-subject factors, showed that neither the main effect nor the interactions involving the order factor were significant, except for an order × material × motion pattern interaction ($F(1,28) = 10.19$, $p < .005$, $\eta_G^2 = 0.013$) and the four-way interaction ($F(4,112) = 4.51$, $p < .005$, $\eta_G^2 = 0.004$). The statistical significance of both interactions appears to be due to a more marked material × magnitude crossover interaction (for the uniformly accelerated motion) in the responses of participants who took part in Experiment 2 rather than Experiment 1 first.

vertically downward with a fairly high degree of accuracy (see Zago & Lacquaniti, 2005); Secondly, sensitivity to optical information that specifies the object's time of arrival at the point of interception (Lee, Young, Reddish, Lough, & Clayton, 1983), taken alone, cannot account for the high level of accuracy observed in such interceptive actions, which suggests that an internalized model of gravity assists interceptive actions (Lacquaniti & Maioli, 1989; Zago et al., 2008; Zago & Lacquaniti, 2005). However, there is no agreement among researchers on the latter point. For instance, according to Baurès et al. (2007) the results of interceptive actions studies would not support the use of an accurate internal model of gravity, but they would rather support the use of optical information coupled with approximate qualitative knowledge of gravity (cf. Zago et al., 2008). Similarly, the results obtained by Baurès, Benguigui, Amorim, and Hecht (2009) suggest that the interception of vertically falling real and virtual balls was likely driven by first-order optical information, rather than by the 1 *g* model. Zhao and Warren (2015) reviewed the results of a number of motor tasks studies, and argued that action is driven by internal representations of the outer world only when visual information is unavailable or degraded, whereas in 'normal' viewing conditions action would be driven by visual information. Even assuming that, at least in some circumstances, the manual interception of vertically falling objects is driven by an internalized model of gravity, it remains unclear whether the 1 *g* model may also drive participants' performance in other types of tasks. For instance, the results obtained by Gravano et al. (2017) suggest that the 1 *g* model does not underlie the imagined vertical fall of an object, and the results of Experiment 1 suggest that the 1 *g* model did not drive participants' perceptual judgments of simulated vertical falls. As regards PM tasks, Zago et al. (2010) found that TTC estimations in a PM task with short TTCs were driven by the 1 *g* model, whereas the results of our Experiment 2 showed that, with longer TTCs, this was not the case. Besides differences in occlusion periods, our Experiment 2 and Zago et al.'s (2010) study also differ in several aspects related to the experimental settings, such as the viewing distance and the type of simulated falling object (i.e., simulated material spheres in the former, a featureless shape in the latter). Further studies appear to be needed in order to clarify which of the differences between the two experiments may be responsible for the observed differences in the patterns of results, and, more in general, in order to define the extents and the limits of the 1 *g* model.

As a final note, it appears that the results of Experiments 1 and 2 raise an interesting observation with respect to our intuitive understanding of physical events. That is, that our understanding of physical phenomena might dramatically differ from the actual phenomena to the extent that such an understanding might work on a local rather than on a global level. Indeed, all physical phenomena concerning the motion of macroscopic objects, can be described within the framework of classical Lagrangian and Hamiltonian mechanics (see, e.g., Landau & Lifshitz, 1976), in terms of global laws that are comprehensive of all the main features of the motion. By virtue of the techniques of variational calculus, the equations of motion of macroscopic objects can be obtained by the so-called principle of least action as the solutions minimizing some abstract quantity with the dimensions of an energy per time (Action). Typically, the entire motion comes out as the one that fulfils the best possible physical conditions given the elements in play, meaning that it requires the lower amount of energy in time to happen. Although such an approach works at a physical level – and has been recently (albeit with very strong limitations) been suggested at a neurophysiological and psychophysical level (Noventa & Vidotto, 2012) – it might appear that such global behaviour is violated at the perceptual and behavioural level. In the previous experiments, indeed, there is a certain degree of evidence that the motion is not processed in its entirety, but that its intuitive understanding is focused on specific features whose relevance can change depending on the task at hand. For instance, the different motion patterns are not considered in Experiment 1, in spite of the need to judge naturalness, but they are a main factor of discrimination in Experiment 2, where a prediction is involved. Yet, these feature selection elements do not preclude that the physical approach might still apply at the local level. It appears indeed that, although our understanding of the physical events might violate physical constraints, it still might obey to specific laws.

Author's note

Original materials used to conduct the research will be made available upon request. Raw data can be downloaded from here: https://osf.io/z45t2/?view_only=95743205eb5d47619855e836f96d7c9a

Appendix A

Because of air resistance, the acceleration of an object that falls in Earth's atmosphere is smaller than the nominal value of 1 *g* (i.e., $g = 9.80665 \approx 9.81\ \text{m/s}^2$), and is not uniform as it decreases with time following the square of the velocity. The decrease in acceleration due to the presence of air resistance depends on the mass: the heavier the object, the smaller the decrease in acceleration. Indeed, from Newton's laws of motion (excluding buoyancy effects) one can then derive the relation

$$a = \frac{w - F_d}{m} \tag{1}$$

where a, w, and m are respectively the object's acceleration, weight, and mass, and F_d is the force implied by the air drag (see Baurès et al., 2007). The entity of the drag is however established by Reynolds number which is given by $Re = \frac{\rho v L}{\eta}$, where $\rho = 1.2047 Kg/m^3$ is the density of air at 20 °C, v is the velocity of the moving objects, L is a linear dimension (in the case of a sphere its diameter $L = 0.065$ m), $\eta = 1.8205 \times 10^{-5} Kg/m * s$ is the dynamic viscosity of air. A Reynolds number lower than one means a linear drag effect, which would be the case if $v \le 2.32 \times 10^{-4} m/s$. This is not satisfied in the case of 6.5 cm diameter wooden and polystyrene spheres falling from a height of 2.20 m. Hence, the spheres are subjected to a drag effect that is proportional to the square of the velocity. One can then write:

$$a(t) = g\left(1 - \frac{v(t)^2}{v_\infty{}^2}\right). \tag{2}$$

This equation means that the effective acceleration $a(t)$ at the instant t of the motion of a real sphere that falls through air from a height of 2.20 m is given as a function of the velocity $v(t)$ and the terminal velocity v_∞, that is, the maximum velocity that can be reached when moving through a physical medium and is defined by the following equation:

$$v_\infty = \sqrt{\frac{2mg}{\rho C_d A}} \tag{3}$$

where m is the sphere's mass, ρ is the density of the medium, C_d is the drag coefficient (i.e., 0.47 for a sphere in the range of Reynolds number that we require), and A is the cross-sectional area of the sphere.

Now, if one considers a free fall in the vacuum, the motion equations are given by $v(t) = gt$ and $s(t) = .5gt^2$. For a fall from a height of 2.20 m, the maximum velocity is given by $v_M = 6.56991$ m/s, and it is independent of the object mass. The motion happens in a temporal interval of $t = 657$ msec. Interestingly, according to Eq. (3), both the terminal velocity v_∞ for the wooden sphere (i.e., 23.97145 m/s) and the terminal velocity v_∞ for the polystyrene sphere (i.e., 7.22766 m/s) are higher than the maximum velocity reached after a 2.20 m fall in the vacuum. This implies that wooden and polystyrene spheres that fall from a height of 2.20 m do not reach their terminal velocity. Because the values of v_∞ for the wooden and polystyrene spheres are different, we can draw an important implication of Eq. (2). The effective gravitational accelerations of both spheres decrease with time, because $v(t)^2$ increases with time, whereas $v_\infty{}^2$ remains constant for a given sphere, but with a different pace. In particular, the wooden sphere experiences an effective acceleration in the range $a(t) \in [.92g, g]$, while the polystyrene sphere experiences an effective acceleration in the range $a(t) \in [.12g, g]$.

The motion equations for the velocity and the position of the vertical fall comprising the effect of the drag are given by

$$v(t) = v_\infty \tanh\left({}^{gt}\!/_{v_\infty}\right) \tag{4}$$

and

$$s(t) = \left({}^{v_\infty{}^2}\!/_{g}\right)\, log\left(\cosh\left({}^{gt}\!/_{v_\infty}\right)\right) \tag{5}$$

By solving Eq. (5) with respect to t for $s = 2.20$ m and given the initial condition $s(0) = 0$ one can derive the time needed for the entire fall to happen, which is respectively $t = 674$ msec for the wooden sphere, and $t = 717$ msec for the polystyrene sphere. If one considered these two time intervals as if the motion were uniformly accelerated, it would require respectively the uniform accelerations $a = 9.688\ \mathrm{m/s^2}$ for the wooden sphere and $a = 8.567\ \mathrm{m/s^2}$ for the polystyrene sphere to cover the same vertical distance. Since the corresponding ratios to g are 0.988 and 0.873 a choice of $\approx 0.9\,g$ was used to approximate the gravitational uniform acceleration for both materials.

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