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Intuitive physics of free fall: an information integration approach to the mass-speed belief

Michele Vicovaro*

University of Padua, Italy

In this study, the intuitive physics of free fall was explored using Information Integration Theory and Functional Measurement. The participants had to rate the speed of objects differing in mass and height of release at the end of an imagined free fall. According to physics, falling speed increases with height of release but it is substantially independent of mass. The results reveal that the participants hold a strong mass-speed belief, i.e., they believe that heavier objects fall faster than lighter ones. Mass and height of release are integrated according to a multiplicative rule. The results are interpreted as providing support to the hypothesis of the perceptual-motor origin of the mass-speed belief. Implications of the results for physics education are discussed.

History books tell us that when Galileo Galilei (1564 - 1642) was still a young mathematics teacher, he conducted a brilliant demonstration for his students and colleagues. He dropped pairs of objects of the same material but different masses from the top of the famous leaning tower of Pisa, and showed that they fell with the same acceleration touching the ground simultaneously (Drake, 1978)[1]. Actually, this famous account of Galileo's demonstration is probably inaccurate because on Earth, when objects are dropped from the top of buildings or towers (as it was the case of Galileo's demonstration), heavier objects fall slightly faster than lighter ones because

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* Michele Vicovaro, email: vicovaro85@gmail.com

[1] Galileo's demonstration is perhaps the most famous, and according to Drake (1978) it probably took place around 1590. However, a similar demonstration was conducted a few years before by Simon Stevin (1548 - 1620), who dropped pairs of objects from the top of the tower of the New Church in Delft, and obtained the same results as Galileo (ibid.). It is worth noting that some scholars argue that Galileo's demonstration never occurred, and that it was only a thought experiment.

of the effect of air resistance (see Oberle, McBeath, Madigan, & Sugar, 2005 for a detailed discussion)[2].

The Italian Jesuit astronomer Giovanni Battista Riccioli (1598 - 1671) was probably the first 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 meters high. The heavier ball touched the ground 0.83 s before the lighter one. On the one hand, these data confirm that falling speed increases with mass from a physical viewpoint (because of the effect of air resistance) but, on the other hand, they reveal that the effect of mass on falling speed is very small.

Riccioli's data reveal that for a relatively high point of release (85 m), large differences in mass produce relatively small differences in time of contact with the ground (less than one second). For the properties of uniformly accelerated motion, this difference will tend to decrease with the lowering of the height of release. If the two clay balls of Riccioli's experiment had been released from one meter or two, then the difference in the time of contact with the ground would have been approximately null. Therefore, the account of Galileo's demonstration (i.e., all objects dropped simultaneously from the same height touch the ground simultaneously, irrespectively of their mass) is a good description of the behavior of free falling objects in most everyday life events, where the height of release barely exceeds one meter or two[3].

Intuitive physics of free fall

Free fall is a common physical phenomenon, with which even people who do not have formal instruction in physics are quite familiar. For the purposes of the present study, I consider two basic features of the phenomenon. The first, which obviously results from the properties of

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[2] Only in the vacuum all objects fall exactly with the same acceleration irrespectively of their mass, as it was demonstrated by Commander David Scott during the Apollo 15 lunar mission. The demonstration showed that on the Moon, where the effect of air resistance is absent, a hammer and a feather fall to the ground with the same acceleration. This confirmed empirically the Galilean theory of free fall. The reader can find the video of this experiment on the web, typing on a search engine 'The hammer and the feather' (http://www.youtube.com/watch?v=5C5_dOEyAfk).

[3] This might not be the case when objects differ not only in mass, but also in size, shape, and material. The overall effect of air resistance on these variables may result in large differences in falling speeds. For instance, the reason why on Earth a hammer falls much faster than a feather is that the latter is characterized by a combination of properties that maximize the effect of air resistance.

uniformly accelerated motion, is that the speed of an object at the end of a free fall (final speed) increases with its height of release. The second is that final speed is substantially independent of mass, at least for heights of release with which people are familiar (see the discussion above). It seems plausible to hypothesize that, thanks to abundant experience, people should have a good intuitive knowledge of these simple facts. However, empirical evidences show that this is not the case.

Researchers in science education have long started exploring students' understanding of the concepts of gravity and free fall (see Kavanagh & Sneider, 2007 for a review); some of these studies showed that the majority of people without formal instruction in physics (or with only elementary instruction in the subject) believe that heavier objects fall faster than lighter ones (Champagne, Klopfer, & Anderson, 1980; Oberle et al., 2005, Experiment 1; Shanon, 1976). Rohrer (2002) called this misconception the *mass-speed belief*. Sequeira and Leite (1991) showed that 52% of a sample of fourth-year university physics students reasoned according to the mass-speed belief: this reveals that the belief is quite impervious to physics instruction, and that it is very resistant to change. Studies on the intuitive physics of inclined planes also support the pervasiveness of the mass-speed belief: most people believe that the speed of an object descending along an incline increases with its mass (Halloun & Hestenes, 1985; Karpp & Anderson, 1997; Proffitt, Kaiser, & Whelan, 1990).

The intuitive relation between mass and falling speed has been investigated almost exclusively using paper-and-pencil tests (Champagne et al., 1980; Sequeira & Leite, 1991; Shanon, 1976). Typically, in these tests the participants are presented with the following problem: there are two objects with different masses, which are released simultaneously from the same height. Which one will fall faster? As discussed above, participants in large majority usually respond 'the heavier one'. Although these tests provide hints of the existence of the mass-speed belief, they explore the understanding of the phenomenon only in a qualitative way, and do not clarify whether the belief occurs only for large heights of release, or whether it also occurs for small heights of release. This distinction is critical, because in the former case the participants' responses would be at least partially consistent with physics, whereas in the latter they would not (see the discussion above on Riccioli's experiment). Therefore, the consistency between intuitive and normative physics of free fall should be assessed through the study of the conceptions of the *quantitative relation* between falling speed, mass, and height of release.

First aim of the study: exploring the intuitive relation between falling speed, mass, and height of release using Information Integration Theory and Functional Measurement

The first aim of the present study was to explore participants' conceptions of the quantitative relation between falling speed, mass, and height of release. Information Integration Theory (IIT) and Functional Measurement (FM) constituted the theoretical and methodological frameworks of the study. The participants were asked to imagine the free fall of objects differing in mass and height of release, and were asked to rate their imagined speed at the end of the fall. Height of release did not exceed 2.25 m: as previously discussed, from such relatively small heights all objects fall to the ground approximately with the same acceleration, irrespectively of their mass.

According to IIT, people integrate stimulus information using simple algebraic rules. When required judgments about social or physical events, people typically transform the cues available in the stimulus into corresponding psychological variables, which are then integrated according to additive, multiplying, or averaging rules (Anderson, 1981). FM provides the methodological framework for the assessment of cognitive algebraic integration rules (Anderson, 1982). Because several physical laws (e.g., Newton's laws of motion) are formalized as simple algebraic rules, IIT and FM may be useful tools for directly comparing cognitive and physical rules. For instance, researchers have used IIT and FM to directly compare cognitive and physical integration rules of inclined planes (Karpp & Anderson, 1997), sliding friction (Corneli & Vicovaro, 2007), elasticity (Cocco & Masin, 2010), buoyancy (Masin & Rispoli, 2010), electric circuits (Chasseigne, Giraudeau, Lafon, & Mullet, 2011; Liégeois, Chasseigne, Papin, & Mullet, 2003), projectiles motion (Krist, Fieberg, & Wilkening, 1993) and collisions (De Sá Teixeira, De Oliveira, & Viegas, 2008; Vicovaro, 2012).

Second aim of the study: testing the hypothesis of the perceptual-motor origin of the mass-speed belief

The second aim of the present study was to test the hypothesis that the mass-speed belief has a perceptual-motor origin. When we hold an object in hand, the object exerts a downward force on the hand called weight. Weight is the product of mass and of gravitational acceleration (*g*). Therefore, the object pushes the hand downward with a force proportional to its mass[4]. However, an object in free fall has no weight, and its speed depends only on gravitational acceleration, not on mass (except for the small effect of air resistance)[5]. My hypothesis is that the mass-speed belief occurs because people *extend* their perceptual-motor experience of holding objects in hand to free fall. Implicitly, they believe that after an object has been released in free fall, it would continue to exert a downward force proportional to its mass, as it did while it was supported by their hand. Therefore, they expect that heavier objects are subject to forces stronger than those acting on lighter objects, and thus fall down more quickly.

Various researchers in the field of intuitive physics have suggested that some misconceptions in the understanding of physical events may depend on perceptual-motor experience (e.g., diSessa, 1993; Rohrer, 2002; Yates, Bessman, Dunne, Jertson, Sly, & Wendelboe, 1988). A hypothesis similar to that discussed here was proposed by Hecht and Bertamini (2000) for explaining misconceptions in the intuitive physics of throwing actions. The authors found that the participants incorrectly believed that a projectile would continue to accelerate for a while after it left the hand of the thrower, whereas according to physics it should start decelerating as soon as it leaves the hand of the thrower. The authors suggested that this misconception would originate from the 'externalization of body dynamics': because the arm of the thrower accelerates during the throwing motion, people would implicitly extend the acceleration of this body part to the subsequent motion of the projectile (see also Hecht, 2001).

EXPERIMENT

The participants were asked to imagine the free fall of an object, and to rate its imagined speed at the end of the fall. The mass of the object and its height of release were manipulated according to a factorial design. The experiment was composed of two distinct conditions. In the *vision only condition* the participants could not touch the stimulus while imagining its free fall, and thus the downward force (weight) exerted by the stimulus on their hand could not be directly perceived. Conversely, in the *vision + touch condition* the weight exerted by the stimulus on the participants' hand was immediately perceivable, because the participants were allowed to hold the stimulus in hand while imagining its free fall. In the latter condition, the

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[4] This downward force (weight) is part of the sensation of heaviness (Ross & Brodie, 1987).

[5] As suggested by Galili (2001), I rely on an 'operational' rather than on a 'gravitational' definition of weight.

greater perceptual saliency of weight allowed the participants to focus more attention on that dimension. Therefore, the participants in this condition should be more prone to *extend* their perceptual-motor experience of the weight exerted by the stimulus on their hand to the imagined free fall of the stimulus itself. In other words, if the hypothesis of the perceptual-motor origin of the mass-speed belief is correct, then the mass-speed belief should be greater in the *vision + touch condition* than in the *vision only condition*.

METHOD

Participants. The participants were 50 voluntary students of Psychology. They all had normal or corrected-to-normal visual abilities. Half of them, aged between 20 and 30 (M = 23.6, SD = 2.72, 9 males) participated in the *vision only condition*, whereas the other half, aged between 20 and 30 (M = 24.1, SD = 3.02, 10 males) participated in the *vision + touch condition*. The two groups were similar in years of physics instruction, as on average the participants in the *vision only condition* and the participants in the *vision + touch condition* had studied physics for 2.64 years (SD = 1.78) and 2.6 years (SD = 1.70) respectively.

Stimuli. The stimuli were three cubic cardboard boxes with a side of 10 cm. The masses of the boxes were 20 g, 120 g, and 220g respectively. Each box was uniformly filled with a certain amount of plasticine to obtain the required mass. The 20 g box was yellow, the 120 g box was red, and the 220 g box was blue.

Procedure and Experimental Design. Prior to the experiment, the participants read and signed informed consent form approved by the local ethics committee (Department of General Psychology, University of Padua). The participants were tested individually. They were seated at a distance of about two meters from a white wall, their face directed toward the wall. Three yellow numbered markers were attached on the wall. Markers number one, two, and three were attached at a height of 0.55 m., 1.4 m, and 2.25 m from the ground respectively. The number of each marker was written inside the marker itself, and was clearly visible to the participants. The stimuli (i.e., the cardboard boxes) rested on the surface of a small table located beside the chair where the participants were seated.

The instructions informed the participants that during the experiment they had to imagine to release the boxes from the height corresponding to one of the three markers attached on the wall. They were then specified that they had to imagine to release the box, and not to throw it to the ground. Then, they were told that they had to rate the speed that the box would have reached one instant before touching the ground using an integer number between 0 and 100. Instructions specified that 0 corresponded to a null speed (a stationary object), and 100 to a very high speed (a bullet shot downward). After this, the experimenter informed the participants that the yellow, red, and blue boxes had a mass of 20 g, 120 g, and 220 g respectively. The participants were provided a paper (mass paper) which indicated the mass of each box, in the case they forgot this information during the course of the experiment. In order to obtain a rough idea of the heaviness of the boxes, they were allowed to touch and hold in hand each box for a few seconds before starting the experiment.

During the experiment, the participants in the *vision only condition* were not allowed to touch the stimuli: on each trial, the experimenter communicated verbally the color and the number which corresponded respectively to the box and the marker. It is worth emphasizing that the participants could not hold the box in hand while imagining its free fall and rating its imagined speed, and therefore they could not perceive directly the weight of the box.

In contrast, the participants in the *vision + touch condition* were allowed to hold in hand the box while they imagined its free fall and rated its imagined final speed. On each trial, the experimenter put one of the three boxes on the participants' favorite hand, and then specified verbally the number of the marker to indicate the corresponding height of release. While they held the box in hand, the participants could move their hand, wrist, and arm as they wanted, but had to remain seated on the chair. After the participants had rated the imagined speed, the experimenter took the box from their hand, put it on the table, and then proceeded to the next trial.

The experiment followed a 3 (Mass) × 3 (Height of release) × 2 (Condition) factorial design, with 'Mass' and 'Height of release' as within participants factors, and 'Condition' as between participants factor. In each of the two conditions, the nine stimuli were presented three times each in random order. Five additional practice stimuli were presented before the experiment.

After the experiment, the participants were presented with a brief questionnaire which investigated their general knowledge of free fall. Specifically, they were asked to predict what happens to the falling speed of an object when its mass increases and when its height of release increases.

RESULTS

I am going to present the results of the comparison between the two conditions first, followed by the results of the two distinct conditions, and by the results of the post-experimental questionnaire.

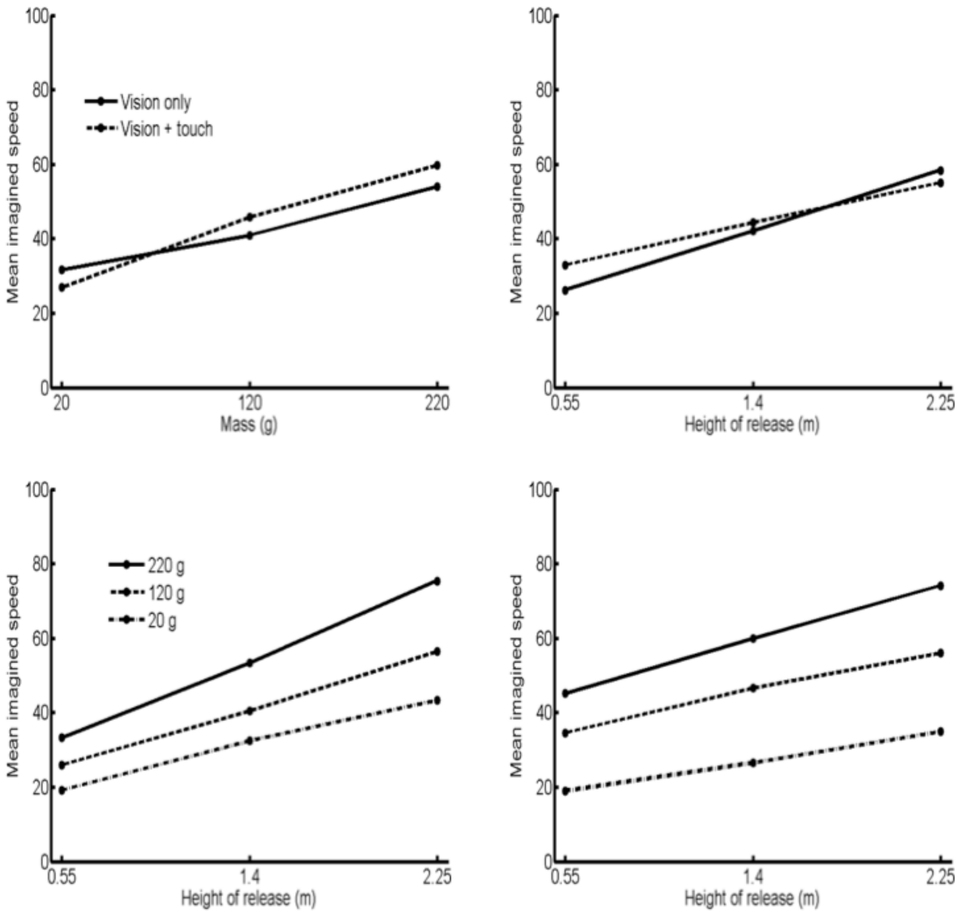

Figure 1. Top left: Mean imagined speed of the stimuli at the end of the free fall averaged over height of release as a function of mass for each experimental condition. Top right: Mean imagined speed of the stimuli at the end of the free fall averaged over mass as a function of height of release for each experimental condition. Bottom panels: Mean imagined speed of the stimuli at the end of the free fall as a function of height of release (horizontal axis) and mass (separate lines), in the 'vision only condition' (bottom left) and in the 'vision + touch condition' (bottom right).

Comparison between 'vision only condition' and 'vision + touch condition'. The top left panel of Figure 1 shows the mean rated speed averaged over height of release for the three levels of mass (horizontal axis) for each condition (separate lines). In turn, the top right panel shows the mean rated speed averaged over mass for the three levels of height of release (horizontal axis) for each condition (separate lines). The line corresponding to the *vision + touch condition* is slightly steeper in the top left panel and slightly flatter in the top right panel, as compared with the line corresponding to the *vision only condition*. This suggests that mass exerted a slightly stronger influence and height of release exerted a slightly smaller influence on imagined speed in the *vision + touch condition*.

In order to test these evidences statistically, I performed a 3-way mixed-effect ANOVA on the mean rated speed with within-participants factors *Height of release* and *Mass* and between-participants factor *Condition*. Here the focus is on differences between the two experimental conditions, therefore I discuss only the main and interaction effects involving 'Condition' factor. Its main effect was not significant ($F(1,216) = 1.21$, $p = 0.27$, $\eta^2 = 0.001$). A significant main effect of this factor could mean that in one of the two conditions the participants were biased toward a general overestimation or underestimation of the imagined speed, but this was not the case. The two-factor interaction Condition × Height of release was marginally significant ($F(2,216) = 2.82$, $p = 0.06$, $\eta^2 = 0.007$), whereas the two-factor interaction Condition × Mass was significant ($F(2,216) = 3.79$, $p = 0.02$, $\eta^2 = 0.01$). These two-factor interactions provide statistical support to the results illustrated in the top panels of Figure 1: mass exerted a slightly stronger influence and height of release exerted a slightly smaller influence on imagined speed in the *vision + touch condition* than in the *vision only condition*. Finally, the three-factor interaction was not significant ($F(4,216) = 0.11$, $p = 0.98$, $\eta^2 < 0.001$). In order to determine how the participants integrated mass and height of release when asked to judge imagined speed I analyzed separately the results obtained in the two conditions.

Vision only condition. The bottom left panel of Figure 1 shows the mean rated speed for the height of release (horizontal axis) and the mass (separate lines) of each box. Three diverging lines fit the data, and according to the linear fan theorem of FM (Anderson, 1982) this supports the hypothesis of a multiplicative integration for mass and height of release. Thus, in the *vision only condition* the participants appear to use the following cognitive integration rule:

$$Imagined\ Speed = Mass \times Height\ of\ release \quad (1)$$

A two-way repeated measures ANOVA was performed to test Equation (1). The main effect of factor Mass was significant ($F(2,48) = 40.40$, $p < 0.001$, $\eta^2 = 0.15$), as well as the main effect of factor Height of release ($F(2,48) = 119.87$, $p < 0.001$, $\eta^2 = 0.32$). Their interaction effects were also significant ($F(4,96) = 22.51$, $p < 0.001$, $\eta^2 = 0.02$), with the linear-by-linear component being the only significant one ($F(1,96) = 85.46$, $p < 0.001$, $\eta^2 = 0.02$). This pattern of statistical results is consistent with Equation (1) (see Anderson, 1982, p. 117).

Individual data were plotted in the same manner as group data, and visual inspection of the graphs indicated that the multiplicative integration rule was used consistently by the participants. The multiplicative rule was used by 20 out of 25 participants. Of the remaining participants, only three used the physically correct height-only rule. One participant used an additive integration rule, and one an inverted multiplicative rule, with imagined speed decreasing with the mass of the object.

Vision + touch condition. The bottom right panel of Figure 1 shows the mean rated imagined speed for the height of release (horizontal axis) and the mass (separate lines) of each box. Three diverging lines fit the data, and this supports a multiplicative rule for the integration of mass and height of release. Thus, it appears that the participants used the same cognitive integration rule as in the *vision only condition* (see Equation (1)).

A two-way repeated measures ANOVA was performed to test Equation (1). The main effect of factor Mass was significant ($F(2,48) = 110.01$, $p < 0.001$, $\eta^2 = 0.30$), as well as the main effect of factor Height of release ($F(2,48) = 53.21$, $p < 0.001$, $\eta^2 = 0.14$). Their interaction effects were also significant ($F(4,96) = 14.85$, $p < 0.001$, $\eta^2 = 0.01$), with the linear-by-linear component being the only significant one ($F(1,96) = 57.82$, $p < 0.001$, $\eta^2 = 0.01$). This pattern of statistical results is consistent with Equation (1) (see Anderson, 1982, p. 117).

Individual data were plotted in the same manner as group data, and visual inspection of the graphs indicated that the multiplicative integration rule was used consistently by the participants. The multiplicative rule was used by 21 out of 25 participants. Of the remaining participants, one used a mass-only rule, and three used a somewhat indefinite integration rule.

Post-experimental questionnaire. The answers to the post-experimental questionnaire revealed that the participants in the two experimental conditions had similar general knowledge of free fall. Numbers in brackets indicate the frequency of responses in the *vision only condition*. When asked what happens to the falling speed of an object when its mass increases, 43 over 50 participants (21) reported that it increases. Among the remaining participants, five (three) reported that it remains unchanged, and two (one) that it decreases. When asked what happens to the falling speed of an object when its height of release increases, 46 participants (23) responded that it increases. Among the remaining participants, two (one) responded that it remains unchanged, and two (one) that it decreases. Individual responses to the post-experimental questionnaire were consistent with the information integration rules used by the participants in the rating task.

DISCUSSION

The first aim of the study was to explore participants' conceptions of the quantitative relation between falling speed, mass, and height of release. Analyses conducted in the framework of IIT and FM revealed that, in both experimental conditions, the imagined speed of an object at the end of a free fall depended on a multiplicative integration between mass and height of release. Measures of the effects size (η^2), showed that the main effect of variable mass was large in both conditions as compared with that of variable height of release (in particular in the *vision + touch condition*). This is also evident from visual inspection of the bottom panels in Figure 1. It is worth remembering that, for the heights of release considered in the present study, mass exerts a negligible influence on falling speed from a physical viewpoint. This leads to the conclusion that participants' intuitive physics of free fall strongly deviates from normative physics as regards the effect of mass on falling speed.

The comparison between the *vision only condition* and the *vision + touch condition* revealed that the mass-speed belief was stronger in the latter, as the imagined speed of the stimuli was more influenced by mass and less influenced by height of release as compared with the former. Importantly, this could not be due to differences in the composition of the two experimental groups, which were similar not only in gender and age, but also in years of physics instruction and general knowledge of free fall, as revealed by the results of the post-experimental questionnaire. This result lends support to the hypothesis of the perceptual-motor origin of the mass-speed belief. Indeed, the belief was stronger in the *vision + touch* condition, where the perceptual-motor experience of weight could be *extended* more easily to the imagined free fall of the stimuli because of the greater perceptual saliency and the greater attention to the dimension of weight.

Nevertheless, the results of the *vision only condition* showed that the mass-speed belief was strong even when the participants could not perceive directly the weight of the stimuli. This finding is not in contrast with the hypothesis of the perceptual-motor origin of the belief. Indeed, in both conditions the participants were allowed to feel the weight of each stimulus before starting the experiment. It seems likely that verbal communication of the mass of the stimulus was sufficient to allow the participants to retrieve from memory the corresponding perceptual-motor representation of its weight, and to *extend* this representation to the imagined free fall of the stimulus. Plausibly, this perceptual-motor representation was weaker and noisier as compared with the actual perceptual-motor experience of weight, and this may explain why the mass-speed belief was weaker than in the *vision + touch condition*. Retrieval from memory of perceptual-motor representations of weight may explain why, in everyday life conditions, the mass-speed belief may occur even when people are provided only with verbal information about mass.

Finally, it is worth noting that though the difference between the results in the two experimental conditions was statistically significant, the size of the effect was quite small, as also confirmed by the top panels in Figure 1. Therefore, the hypothesis of the perceptual-motor origin of the mass-speed belief needs to be confirmed in future studies. For instance, developmental studies might help shedding light on the issue: if the belief has a perceptual-motor origin, then it should appear very early in individual development.

Interacting with free falling objects. That the intuitive physics of free fall deviates from physics as regards the effect of mass on falling speed seems an evolutionary paradox, as interactions with free falling objects such as launching, releasing, and catching are ubiquitous in everyday life, and probably played a major role for the survival of our ancestors. A solution to this apparent paradox is provided by studies showing that people's *interactions* with free falling objects are impervious to the mass-speed belief. In their experiments 2 and 3, Oberle et al. (2005) asked the participants to release two balls which differed in size, mass, or density from the top of a building, so that they would touch the ground simultaneously. The participants tended to release the two balls differing in mass at the same time, so that the two balls effectively touched the ground almost simultaneously. Lacquaniti and Maioli (1989) asked the participants to catch a ball released from above their hand, and varied the mass and the height of release of the ball. They found that the timing of the muscular activity associated with the catching motion depended on height of release but was independent of mass: this allowed a timely catch of the ball. Zago and Lacquaniti (2005) hypothesized that, differently from the cognitive system, the motor system relies on an internal representation of free fall which is consistent with physics.

Implications for physics education. The results of the present study have important implications for physics education. As shown by Clement (1982), misconceptions about elementary physics are quite impervious to formal instruction and have a detrimental effect on students' understanding of the subject. McDermott (1991) pointed out that, unless students' misconceptions are specifically addressed, the new notions presented by the teacher will be distorted and accommodated to the pre-exiting misconceptions. For what concerns the teaching of the physics of free fall, only after the mass-speed belief has been addressed the students will be ready to acquire the correct physical principles.

I suggest that a potentially valid strategy for improving the teaching of the physics of free fall is that of discussing with students the hypothesis of the perceptual-motor origin of the mass-speed belief. This should emphasize the distinction between two contiguous but fundamentally different physical situations: when an object is held in hand, and thus subject to forces, and when an object is in free fall, and thus subject only to gravitational acceleration. In addition, it is likely that students would benefit of functional learning, i.e., a procedure which help students to learn correct integration rules through the use of cognitive feedback. The procedure has already been proven effective for improving students' understanding of the functional relations between resistance, potential difference, and current in electric circuits (Chasseigne et al., 2011; Liégeois et al., 2003), and may be helpful also in the context of free fall.

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