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The Galileo Bias: A Naive Conceptual Belief That Influences People's Perceptions and Performance in a Ball-Dropping Task

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This research introduces a new naive physics belief, the Galileo bias, whereby people ignore air resistance and falsely believe that all objects fall at the same rate. Survey results revealed that this bias is held by many and is surprisingly strongest for those with formal physics instruction. In 2 experiments, 98 participants dropped ball pairs varying in volume and/or mass from a height of 10 m, with the goal of both balls hitting the ground simultaneously. The majority of participants in both experiments adopted a single strategy consistent with the Galileo bias, showing no improvement across trials. Yet, for participants reporting intentions of dropping both balls at the same time, the differences between release points were significantly greater than 0 ms. These findings support separate but interacting cognition and perception-action systems.

Keywords: induced motion, relative motion, baseball, perception, action

Mark Twain indicated, "It's not what you do not know that hurts you. It's what you know that ain't so!" This quote relates directly to the field of naive physics, which investigates common misconceptions people hold about various aspects of objects and motion in the physical world. One such misconception is the naive belief in curvilinear impetus. For example, when presented with the hypothetical scenario of a ball being shot outward through a spiral tube, half of the participants of one study indicated that the ball would continue to travel in a curved path upon exiting the tube (McCloskey, Caramazza, & Green, 1980). According to Newtonian physics, however, the ball would actually roll along a straight path because of the absence of any external forces. This naive belief remarkably resembles the principle proposed by medieval impetus theorists, that an object set in motion acquires an internal force (i.e., impetus) in the direction of its motion, be it straight or curved (McCloskey et al., 1980; McCloskey & Kargon, 1988). Similarly, the current research shows that people's naive beliefs about the effects of air resistance on objects in freefall resemble some incorrect notions put forth by the legendary scientist, Galileo Galilei.

In *Two New Sciences* (Galilei, 1638/1974), Galileo presented his ideas about falling bodies. On the basis of a clever set of experiments in which he used a water clock to determine the rate at which a ball rolled down a grooved ramp, he showed that all falling bodies accelerate downward at a uniform rate. He further reasoned that, in the absence of air resistance, this rate of acceleration does not depend on an object's volume or mass. With regard to object motion in a natural medium, Galileo argued that the effects of air resistance on most objects are negligible. He wrote,

> Aristotle says that "an iron ball of one hundred pounds falling from a height of one hundred cubits reaches the ground before a one-pound ball has fallen a single cubit." I say that they arrive at the same time. You find, on making the experiment, that the larger outstrips the smaller by two finger-breadths, that is, when the larger has reached the ground, the other is short of it by two finger-breadths. (p. 65)

According to popular legend, Galileo actually performed this experiment from the top of the Leaning Tower of Pisa. However, we know that if volume were held constant, the heavier ball would "outstrip" the lighter ball by many meters, a distance much greater than "two finger-breadths."

Scientists today state that two major forces act on all falling bodies: a downward gravitational force and an upward air resistance force. In regard to the gravitational force, any object dropped in an experimentally contrived vacuum on earth will accelerate downward at the rate of 9.8 $\mathrm{m/s^2}$. Thus, we may say that all objects are affected equally by gravity and that any differences in the rate of freefall in a natural atmosphere are due to differential effects of air resistance.

Air resistance is a force that acts on an object, serving to impede the velocity or acceleration of the object. This force is a function of the following things: the density of air, the object's cross-sectional area, the object's velocity, and the object's drag coefficient (Greenwood, Hanna, & Milton, 1986; Pagonis, Guerra, Chauduri, Hornbecker, & Smith, 1997; Takahashi & Tompson, 1999; Weichman & Larochelle, 1987). The *drag coefficient* is a dimensionless value dependent upon an object's properties, such as surface structure and mass (Greenwood et al., 1986; Pagonis et al., 1997). The current research tests people's beliefs about the differential effects of air resistance on objects varying in volume and mass.

In regard to differences in volume, if everything else were held constant (i.e., shape, surface structure, and mass), increasing the volume of an object would result in an increase in the air resistance force; therefore, air resistance has a greater effect on larger objects

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than on smaller objects. For example, a large ball and a small ball (of identical mass) dropped at the same time from a set height would both begin to accelerate downward as a result of a constant gravitational force. However, because of the differential effects of air resistance, the large ball would accelerate downward at a slower rate than that of the small ball. In addition, the large ball would reach its terminal velocity (when the air resistance force becomes equal to the object's weight) before the small ball (Greenwood et al., 1986; Pagonis et al., 1997; Takahashi & Tompson, 1999; Weichman & Larochelle, 1987). Subsequently, the small ball would hit the ground before the large ball (see Figure 1).

In regard to differences in mass, if everything else were held constant (i.e., shape, surface structure, and volume), increasing the mass of an object would result in a decrease in the drag coefficient and, consequently, a decrease in the air resistance force; therefore, air resistance has a greater effect on lighter objects than on heavier objects. For example, in the dropped ball scenario, a light ball would accelerate downward at a slower rate than a heavy ball (of identical volume), and the light ball would reach terminal velocity before the heavy ball (Greenwood et al., 1986; Pagonis et al., 1997; Takahashi & Tompson, 1999; Weichman & Larochelle, 1987). Subsequently, the heavy ball would hit the ground before the light ball (see Figure 1).

The naive physics literature regarding people's conceptual knowledge of these differential effects of air resistance is scarce. In fact, on the majority of the questions on both the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992) and the Mechanics Diagnostic Test (Halloun & Hestenes, 1985b), two similar comprehensive tests of people's beliefs about object motion and physical mechanics, participants are instructed to ignore air resistance. In addition, some researchers even ignore air resistance when declaring correct responses to their survey questions about object motion, making a response correct when the physics of the problem is incorrect. For example, on a dropped ball question, researchers claimed that a heavy ball and a light ball of the same size, upon being dropped from the same height, would fall at the same rate and hit the ground at the same time, thus ignoring the differential effects of air resistance (Champagne, Klopfer, & Anderson, 1980; Whitaker, 1983). Regardless, results from these studies were mixed; approximately 80% of participants in the Champagne et al. study reported that the heavy and light balls would hit the ground at the same time, whereas approximately 80% of participants in the Whitaker study reported that the heavy object would fall faster than the light object. Furthermore, one is unable to determine whether participants in the Whitaker study possessed accurate reasoning for their responses; perhaps they falsely believed that the heavy object would fall faster than would the light object because "the heavy object experiences a greater gravitational pull."

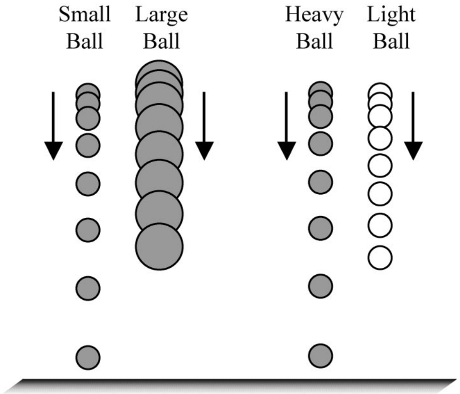

Figure 1. Frame-by-frame natural freefall motion of objects varying in volume but not mass (left) and objects varying in mass but not volume (right). Both the larger and the lighter objects accelerate downward more slowly and reach terminal velocity that is slower and achieved earlier.

Kozhevnikov and Hegarty's (2001) research adds insight into these mixed results while also assessing participants' knowledge of air resistance. They asked participants two questions about heavy and light balls being dropped from the same height. Participants were instructed to take air resistance into account for the first question and to ignore air resistance for the second question. When attending to air resistance, 65% of participants indicated that the heavy ball would hit the ground before the light ball. When ignoring air resistance, though, only 24% indicated that the heavy ball would hit the ground before the light ball. These results suggest that some people do have accurate beliefs regarding the differential effects of air resistance on objects varying in mass.

Evidence from representational momentum (RM) studies also supports the idea that people believe heavy objects fall faster than do light objects (Hubbard, 1995, 1997). In a typical RM experiment, a target moves across a computer screen in a consistent direction and then suddenly vanishes; participants are instructed to indicate the vanishing point. Their responses often involve a forward displacement in the direction of the target's movement, suggesting that people believe the target traveled farther than it truly did. Hubbard examined the effects of perceived weight on displacements of vertically moving square targets. To manipulate perceived weight, he varied the size of the targets. In nature, a positive correlation exists between volume and mass, such that large objects generally have more mass than do small objects. Evidence from size–weight illusion research reflects people's knowledge of this fact (Masin & Crestoni, 1988; Oberle & Amazeen, 2003), and one of Hubbard's experiments did reveal that participants perceived the large targets to be more massive and heavier than the small targets. For all conditions, downward displacements were greater with the heavy targets than with the light targets, suggesting that participants believed that the heavy objects fall faster than did the light objects. However, as with the Whitaker (1983) study, one is unable to know whether participants possessed accurate knowledge regarding the differential effects of air resistance or whether they inaccurately believed that the heavy objects were more affected by gravity than were the light objects. Furthermore, one is unable to differentiate participants' knowledge regarding the motion of falling objects with respect to separate differences in volume and differences in mass.

Although the naive physics research on people's beliefs regarding the motion of falling objects is plentiful, past research on people's beliefs about air resistance, a force with which we all have everyday experiences, is scarce. Furthermore, with what little research has been done, the results are mixed and ambiguous with respect to people's underlying knowledge of the effects of air resistance. In the current research we aimed to assess participants' conceptual knowledge of the differential effects of air resistance on objects varying in volume and mass and to determine whether these conceptual beliefs were evident in their actions in a ball-dropping task. Although the developmental course of people's beliefs was not examined (i.e., current population was college students), the effects of physics instruction were studied. Finally, the effects of visual input on both performance accuracy and conceptual beliefs was also tested.

Experiment 1

In Experiment 1, participants answered a series of multiple-choice questions assessing their conceptual beliefs about the forces acting on falling bodies that vary in volume and mass.

Method

Participants. Participants included 63 female and 42 male students enrolled in an undergraduate research methods course at Arizona State University. Age ranged from 18 to 43 years ($M = 21.02$, $SD = 2.98$). Of these participants, 38 had taken no physics courses, 41 had taken at least one high school physics course but had not taken any college physics courses, and 26 had taken at least one college physics course. All participants were naive to the specific hypothesis being investigated.

Materials. Materials included a survey containing six multiple-choice questions that assessed participants' knowledge of the relative rates of freefall, air resistance, and gravity (see Appendix). Three questions asked about a small ball and a large ball that weighed the same; the other three asked about a light ball and a heavy ball that were the same size. Practical questions assessing beliefs about different objects in freefall encompassed the following: (Questions 1 and 2) which ball would hit the ground first after both are dropped from a set height. Abstract questions assessing general beliefs about air resistance and gravity encompassed the following: (Questions 3 and 4) which ball is the most affected by air resistance and (Questions 5 and 6) which ball is the most affected by gravity.

Two pairs of plastic balls were also used. One pair consisted of two balls that were identical in mass (81.0 g) but varied in volume (diameter = 3.6 cm and 6.8 cm). The second pair consisted of two balls that were identical in volume (diameter = 5.4 cm) but varied in mass (45.0 g and 146.0 g). Mass was varied independently of volume by filling the balls with cotton and lead weights, with care taken to distribute the cotton and weights evenly throughout each ball. The balls were then sprayed with PlastiDip, a liquid solution that transforms into rubber upon drying, to provide a smooth, uniform surface.

Procedure. Participants were informed that they would be answering questions relating to pairs of balls that varied in either size or weight. Prior to administration of the survey, participants were presented with and allowed to handle (heft) the two pairs of balls, previously mentioned, as example stimuli. Order of pair presentation was counterbalanced across participants. For the survey questions, participants were instructed to answer all questions and to provide their best guess to questions for which they were unsure. Participants were further instructed to answer all questions in order and to not go back and change any answers to previously presented questions.

Results

For each survey question, a multinomial logistic regression test was used to analyze the data. These analyses included tests of the main effects of sex and physics instruction, as well as the interaction between these two subject variables. Although the percentages of each response are reported below, analyses were done on data recoded as correct or incorrect, such that the statistics compared percentage of correct responding with a chance level of 50%.[1] Because of the numerous tests, to correct for alpha inflation, we selected an alpha level of .01.

Questions relating to differences in volume. For the abstract question assessing general beliefs about air resistance, 86% of participants correctly reported that the large ball is more affected by air resistance than is the small ball, 12% reported that air resistance affects both balls equally, and 2% reported that the small ball is more affected by air resistance than is the large ball, $\chi^2(1, N = 105) = 53.57, p < .01$. There was no significant effect of sex, $\chi^2(1, N = 105) = 0.29, p = .59$; physics instruction, $\chi^2(2, N = 105) = 0.04, p = .98$; or Sex × Physics Instruction interaction, $\chi^2(5, N = 105) = 1.88, p = .87$. For the abstract question assessing general beliefs about gravity, 83% of participants correctly reported that gravity affects both balls equally, 11% reported that the large ball is more affected by gravity than is the small ball, and 6% reported that the small ball is more affected by gravity than is the large ball, $\chi^2(1, N = 105) = 48.01, p < .01$. The effect of physics instruction approached significance, $\chi^2(2, N = 105) = 6.94, p = .03$; a slightly higher percentage of those who had previously taken physics courses, compared with those who had not, responded correctly. There was no significant effect of sex, $\chi^2(1, N = 105) = 0.99, p = .32$; or Sex × Physics Instruction interaction, $\chi^2(5, N = 105) = 10.76, p = .06$.

For the freefall question, only 34% of participants correctly reported that the small ball will hit the ground first (after both are simultaneously dropped from the same height), 64% demonstrated a Galileo bias by reporting that both balls will hit the ground at the same time, and 2% reported that the large ball will hit the ground first, $\chi^2(1, N = 105) = 10.37, p < .01$. So, although the vast majority of participants (86%) correctly indicated that the large ball is more affected by air resistance than is the small ball, only about a third of all participants were able to apply this knowledge to the dropped ball problem. Perhaps the participants who believed that both balls would hit the ground at the same time were thinking only about the equivalent effects of gravity and not about how air resistance affects falling objects. There was no significant effect of sex, $\chi^2(1, N = 105) = 0.18, p = .67$; physics instruction, $\chi^2(2, N = 105) = 0.37, p = .83$; or Sex × Physics Instruction interaction, $\chi^2(5, N = 105) = 0.95, p = .97$.

Questions relating to differences in mass. For the question on air resistance, only 42% of participants correctly reported that the light ball is more affected by air resistance than is the heavy ball, 47% reported that air resistance affects both balls equally, and 11% reported that the heavy ball is more affected by air resistance than is the light ball, $\chi^2(1, N = 105) = 2.75, p = .10$. Unexpectedly, physics instruction seemed to be detrimental to one's knowledge; 61% of participants with no instruction, 44% with high school physics instruction, and 12% with college physics instruction correctly reported that the light ball is more affected by air resistance than is the heavy ball, $\chi^2(2, N = 105) = 13.24, p < .01$. There was no significant effect of sex, $\chi^2(1, N = 105) = 1.47, p = .23$. However, there was a significant interaction between sex and physics instruction, $\chi^2(5, N = 105) = 19.62, p < .01$, which can be explained by the fact that for those with no previous physics instruction, a greater percentage of female participants responded correctly; for those who had taken physics courses either in high

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[1] Given that there were three options for each question, chance would normally be set at 33%. However, pilot data revealed that one of the three options for each question was rarely selected. Additionally, the primary aim of the current research was to determine which of two beliefs (i.e., responding that is consistent with correct knowledge vs. responding that is consistent with the Galileo bias) people predominantly held.

school or college, though, there was no effect of sex. For the question on gravity, 55% of participants correctly reported that gravity affects both balls equally, 44% reported that the heavy ball is more affected by gravity than is the light ball, and 1% reported that the light ball is more affected by gravity than is the heavy ball, $\chi^2(1, N = 105) = 1.15$, $p = .28$. There was no significant effect of sex, $\chi^2(1, N = 105) = 0.51$, $p = .48$; physics instruction, $\chi^2(2, N = 105) = 5.10$, $p = .08$; or Sex × Physics Instruction interaction, $\chi^2(5, N = 105) = 9.19$, $p = .10$.

For the freefall question, 61% of participants correctly reported that the heavy ball will hit the ground first (after both are simultaneously dropped from the same height), and 39% reported that both balls will hit the ground at the same time, $\chi^2(1, N = 105) = 5.04$, $p = .03$. So, although the majority of participants indicated that both balls are equally affected by both air resistance and gravity, many still have correct knowledge regarding the behavior of these balls when dropped. There was a significant effect of sex; 76% of the female participants, compared with 38% of the male participants, correctly reported that the heavy ball will hit the ground first, $\chi^2(1, N = 105) = 12.75$, $p < .01$. There was no significant effect of physics instruction, $\chi^2(2, N = 105) = 0.59$, $p = .75$. However, there was a significant interaction between sex and physics instruction, $\chi^2(5, N = 105) = 16.51$, $p < .01$, such that physics instruction had a detrimental effect for the men but not for the women.

Discussion

Results of this survey reveal participants' poor conceptual knowledge in regard to the differential effects of air resistance on objects varying in volume and mass. For the freefall questions, no mention was made of air resistance in order to assess participants' beliefs of natural object motion without their seriously analyzing the various factors as in a physics problem. Perhaps if participants were instructed to take air resistance into account for each problem, performance would have improved. Nevertheless, on the abstract questions asking which ball is the most affected by air resistance, performance was far from perfect, especially for the balls varying in mass. In addition, formal physics instruction seemed to be detrimental to the accuracy of air resistance beliefs. This latter finding, though initially unexpected, is not so surprising considering the fact that most students in elementary physics courses are instructed to ignore air resistance when solving problems.

Experiment 2

The results of Experiment 1 suggest seemingly obvious deficiencies in people's knowledge about the differential effects of air resistance on objects varying in volume and mass. However, we should consider the possibility that people may have correct knowledge of these aspects of the physical environment but that this knowledge may not be accurately assessed through a paper-and-pencil task. The present experiment entailed participants dropping balls, varying in volume and mass, from a set height in a natural environment. The purpose of this experiment is to determine whether participants would employ a cognitive strategy such that their poor conceptual beliefs (as evidenced in Experiment 1) are evident in their actions or whether their perceptual-motor skills will play a significant role and perhaps reveal an underlying correct knowledge about the differential effects of air resistance.

Method

Participants. Participants included 17 female and 33 male students enrolled in an introductory psychology course at Arizona State University. Age ranged from 17 to 23 years ($M = 19.02$, $SD = 1.27$). Of these participants, 20 had taken no physics courses, 21 had taken at least one high school physics course but had not taken any college physics courses, and 9 had taken at least one college physics course. All participants were naive to the purpose of the experiment.

Materials. Three pairs of tennis-style balls were used. For the first pair, the two balls were identical in mass (348.8 g) but varied in volume (diameter = 8.0 cm and 23.4 cm). For the second pair, the two balls were identical in volume (diameter = 8.0 cm) but varied in mass (102.3 g and 419.0 g). For the third pair, the two balls were identical in density but varied in volume (diameter = 5.2 cm and 12.9 cm) and mass (34.8 g and 555.8 g, respectively). Mass was varied independently of volume by filling the balls with cotton and lead weights, with care taken to distribute these materials evenly throughout the balls. In addition, the survey from Experiment 1 was also administered (see Appendix).

Procedure. Participants completed 27 trials, 9 for each pair of balls mentioned above. In each of 9 blocks of trials, ball-pair order was randomized. For each trial, participants held one ball in their right hand and the other in their left hand; right–left position of balls was randomized across trials. To hold each ball, participants used a precision grip, with the thumb and forefinger, on the end of a thin string attached to the ball. Participants were then instructed to rest their forearms on the balcony ledge of the third floor of the psychology building (height = 10.06 m)—to make sure that the bottoms of the two balls were level (string length was varied to ensure this situation)—and to drop the two balls so that they would hit the ground at the same point in time. Visual feedback of the downward acceleration and impact was allowed on each trial. All trials were video-recorded, by use of a digital camera with a refresh rate of 30 Hz, for later data coding. Upon completion of trials, all participants completed the survey, and the final 70% of participants were also asked questions about their expectations and intentions.

Results

The dependent variable recorded on each trial was the time between the two release points. Three sets of two-tailed *t* tests (six total *t* tests) were performed to determine whether the mean time between release points for each ball pair significantly differed from 0 ms and from the optimal time. In addition, three mixed-design analyses of variance, 3 (physics instruction) × 2 (sex) × 9 (trial), were used to analyze the data, one for each ball pair. Finally, a series of multinomial logistic regression tests were used to determine whether participants' actions and the visual feedback they received were beneficial to their conceptual knowledge, which was assessed through the survey questions at the conclusion of the experiment. Because of the numerous tests, we selected an alpha level of .01 to correct for alpha inflation.

Ball pair varying only in volume. For the balls that were different in volume but equal in mass, the large ball is more affected by air resistance than the small ball and should thus be released first. Therefore, the dependent variable was set up such that a positive value indicates that the large ball was dropped first and a negative value indicates that the small ball was dropped first. On the basis of a series of preexperimental test drops (videorecorded by use of a camera with a refresh rate of 30 frames per second), the optimal value is 100.00 ms. Overall, participants dropped the large ball a mean of 25.93 ms ($SD = 28.40$) before the small ball, a value that is significantly greater than 0 ms, $t(49) = 6.45$, $p < .01$, but also significantly less than 100.00 ms, $t(49) = -18.44$, $p < .01$. There was no significant effect of sex, $F(1, 45) = 0.75$, $p = .39$; physics instruction, $F(2, 45) = 0.41$, $p = .67$; or Sex × Physics Instruction interaction, $F(1, 45) = 0.74$, $p = .40$. There was also no significant improvement or change across trials, $F(8, 360) = 0.38$, $p = .93$ (see the top panel of Figure 2), despite the fact that a pilot study revealed that the visual feedback was sufficient to see that the two balls fall differently.[2] Finally, there was no significant Trial × Physics Instruction interaction, $F(16, 360) = 1.23$, $p = .24$, Trial × Sex interaction, $F(8, 360) = 4.51$, $p = .04$, or Trial × Physics Instruction × Sex interaction, $F(16, 360) = 0.54$, $p = .83$.

For this ball pair, of the participants asked about their expectations and intentions, 55% reported that they expected both balls to fall at the same rate and that they subsequently intended to drop both balls at the same time throughout the experiment. This pattern is confirmed by their first, final, and overall mean trial times all resulting in values within one standard deviation of 0 ms (Trial 1, $M = 52.94$ ms, $SD = 106.10$ ms; Trial 9, $M = 23.53$ ms, $SD = 38.67$ ms; overall, $M = 17.43$ ms, $SD = 18.60$ ms). These participants essentially began with and maintained a consistent Galileo conceptual bias. However, the fact that the large ball was still dropped before the small ball suggests that these participants' actions are partly guided by an accurate perceptual-motor knowledge. On a positive note, 13% reported that they expected the balls to fall differently and that they subsequently intended to drop the large ball before the small ball throughout the experiment. This pattern is confirmed by their first, final, and overall mean trial times all resulting in values beyond 1 *SD* above 0 ms (Trial 1, $M = 225.00$ ms, $SD = 152.45$ ms; Trial 9, $M = 75.00$ ms, $SD = 68.72$ ms; overall, $M = 76.85$ ms, $SD = 9.74$ ms). In relation to the lack of a beneficial trial effect, 10% reported that they initially believed the large ball should be dropped first (Trial 1: $M = 55.56$ ms, $SD = 96.23$ ms) but that they then realized that both balls fall at the same rate (Trial 9: $M = 11.11$ ms, $SD = 19.25$ ms). In contrast, however, 22% reported that they initially believed that both balls fall at the same rate (Trial 1: $M = 4.76$ ms, $SD = 35.63$ ms) but that they then realized that the large ball should be dropped first (Trial 9: $M = 38.10$ ms, $SD = 44.84$ ms).

Ball pair varying only in mass. For the balls that were equal in volume but different in mass, the light ball is more affected by air resistance than is the heavy ball and should thus be released first. Therefore, the dependent variable was set up such that a positive value indicates that the light ball was dropped first and a negative value indicates that the heavy ball was dropped first. Based on a series of preexperimental test drops, the optimal value is 200.00 ms. Overall, participants dropped the light ball a mean of 39.85 ms ($SD = 28.06$) before the heavy ball, a value that is significantly greater than 0 ms, $t(49) = 10.04$, $p < .01$, but also significantly less than 200.00 ms, $t(49) = -40.35$, $p < .01$. There was no significant effect of sex, $F(1, 45) = 0.03$, $p = .87$; physics instruction, $F(2, 45) = 1.03$, $p = .37$; or Sex × Physics Instruction interaction, $F(1, 45) = 1.38$, $p = .25$. However, there was a significant effect of trial, $F(8, 360) = 4.39$, $p < .01$. Surprisingly, this effect represented a decrease in performance across trials (see the middle panel of Figure 2), despite the fact that the pilot study revealed that the visual feedback was sufficient to see that the two balls fall differently (see Footnote 2 for details). Finally, there was no significant Trial × Physics Instruction interaction, $F(16, 360) = 0.74$, $p = .75$, Trial × Sex interaction, $F(8, 360) = 1.01$, $p = .43$, or Trial × Physics Instruction × Sex interaction, $F(16, 360) = 1.38$, $p = .21$.

For this ball pair, of those participants asked about their expectations and intentions, 68% reported that they expected both balls to fall at the same rate and that they subsequently intended to drop both balls at the same time throughout the experiment (Trial 1, $M = 15.69$ ms, $SD = 35.59$ ms; Trial 9, $M = 27.45$ ms, $SD = 17.62$ ms; overall, $M = 24.40$ ms, $SD = 8.18$ ms). These participants essentially began with and maintained a consistent Galileo conceptual bias. However, the fact that the light ball was still dropped before the heavy ball suggests that these participants' actions are partly guided by an accurate perceptual-motor knowledge. On a positive note, 8% reported that they expected the balls to fall differently and that they subsequently intended to drop the light ball before the heavy ball throughout the experiment (Trial 1, $M = 83.33$ ms, $SD = 70.71$ ms; Trial 9, $M = 50.00$ ms, $SD = 70.71$ ms; overall, $M = 72.22$ ms, $SD = 7.86$ ms). Finally, in relation to the negative trial effect, 24% reported that they initially believed the light ball should be dropped first (Trial 1, $M = 161.11$ ms, $SD = 170.51$ ms) but that they then realized that both balls fall at the same rate (Trial 9, $M = 11.11$ ms, $SD = 40.37$ ms).

Ball pair varying in both volume and mass. For the balls that were different in volume and mass, but equal in density, the dependent variable was set up such that a positive value indicates that the small, light ball was dropped first and a negative value indicates that the large, heavy ball was dropped first. Based on a series of preexperimental test drops, the optimal value is 33.33 ms. Overall, participants dropped the small, light ball a mean of 52.37 ms ($SD = 35.64$) before the large, heavy ball, a value that is significantly greater than 0 ms, $t(49) = 10.39$, $p < .01$, but also significantly greater than 33.33 ms, $t(49) = 3.84$, $p < .01$. There was no significant effect of sex, $F(1, 45) = 0.27$, $p = .61$; physics instruction, $F(2, 45) = 0.36$, $p = .70$; or Sex × Physics Instruction interaction, $F(1, 45) = 2.57$, $p = .12$. However, there was a significant effect of trial, $F(8, 360) = 2.66$, $p < .01$, representing an increase in performance across trials (see the bottom panel of Figure 2). Finally, there was no significant Trial × Physics In-

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[2] A pilot study with 8 male and 9 female undergraduate psychology students, whose ages ranged from 19 to 37 years, was conducted to determine the validity of the visual feedback. Stimuli included the equal mass–different volume ball pair and the equal volume–different mass ball pair used in Experiment 1. Participants completed two trials, in which the experimenter simultaneously dropped the two balls of each pair from the height of 10 m. On each trial, the participant stood next to the experimenter and, upon watching the balls fall, recorded which ball they believed hit the ground first or whether the balls appeared to hit the ground simultaneously. At no time during the experiment were participants allowed to hold any of the stimuli. For the ball pair varying in volume but not mass, 14 participants correctly reported that the small ball hit the ground before the large ball, 2 participants reported that the two balls appeared to hit the ground at the same time, and 1 participant reported that the large ball appeared to hit before the small ball. For the ball pair varying in mass but not volume, 11 participants correctly reported that the heavy (red) ball hit the ground before the light (purple) ball, 5 participants reported that the two balls appeared to hit the ground at the same time, and 1 participant reported that the light ball appeared to hit before the heavy ball. These results support that for most participants, the visual feedback is sufficient to realize that the stimuli fall differently.

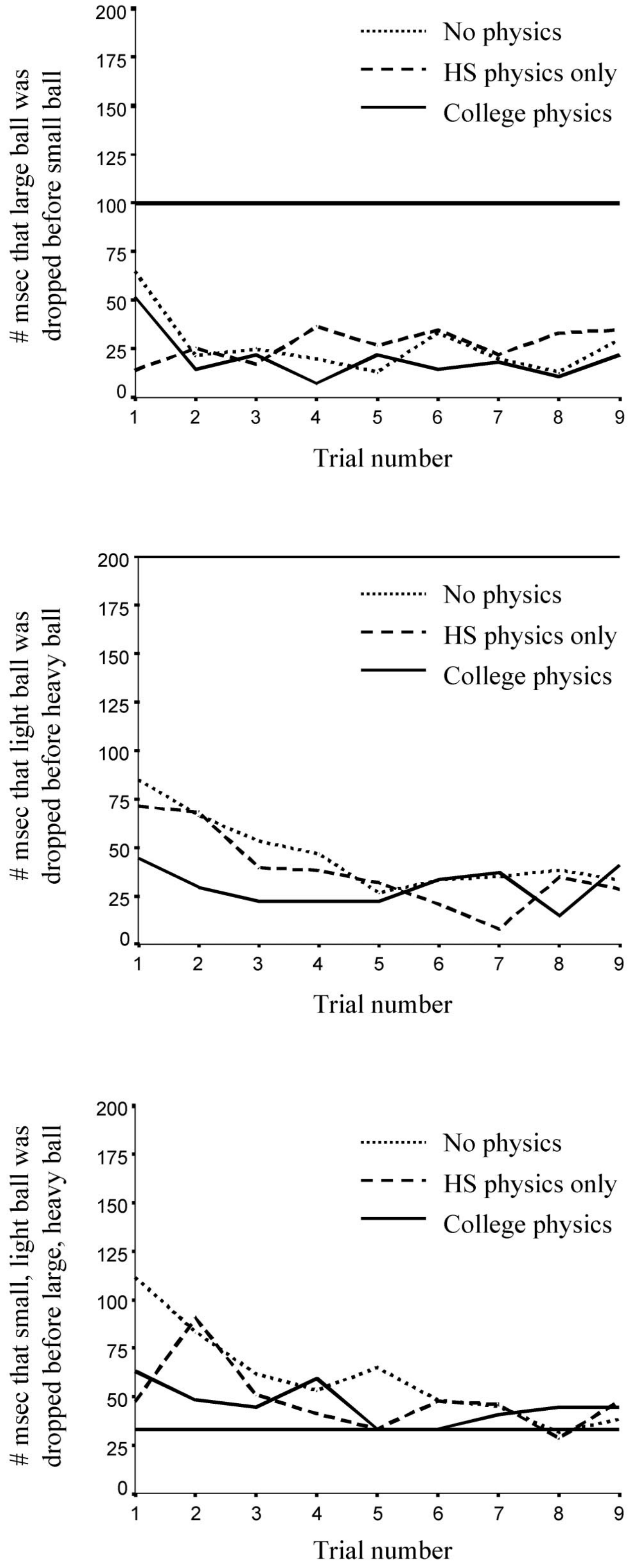

Figure 2. Results of Experiment 2. Mean differences in release times for the equal mass–different volume ball pair (top panel), equal volume–different mass ball pair (middle panel), and different mass–different volume ball pair (bottom panel) as a function of trial and level of physics instruction. The horizontal line in each panel represents the time difference necessary for both balls to reach the ground simultaneously.

struction interaction, $F(16, 360) = 1.34$, $p = .17$, Trial × Sex interaction, $F(8, 360) = 1.16$, $p = .33$, or Trial × Physics Instruction × Sex interaction, $F(16, 360) = 1.01$, $p = .43$.

For this ball pair, of those participants asked about their expectations and intentions, 57% reported that they expected both balls to fall at the same rate and that they subsequently intended to drop both balls at the same time throughout the experiment (Trial 1, $M = 38.89$ ms, $SD = 23.92$ ms; Trial 9, $M = 38.89$ ms, $SD = 12.98$ ms; overall, $M = 36.42$ ms, $SD = 14.29$ ms). In contrast, 14% reported that they expected the balls to fall differently and that they subsequently intended to drop the small, light ball before the large, heavy ball throughout the experiment (Trial 1, $M = 133.33$ ms, $SD = 57.74$ ms; Trial 9, $M = 66.67$ ms, $SD = 0.00$ ms; overall, $M = 71.60$ ms, $SD = 21.38$ ms). Finally, 29% reported that they initially believed the small, light ball should be dropped first (Trial 1, $M = 144.44$ ms, $SD = 232.54$ ms) but that they then realized that both balls fall at the same rate (Trial 9, $M = 33.33$ ms, $SD = 0.00$ ms). These participants provided such comments as, “I expected the really light one to fall a bit slower due to wind because it was so light, but they fell the same.”

Postexperimental survey responses. Comparison of the responses on the postexperimental survey questions with the responses given by participants in Experiment 1 (no action task) revealed a surprisingly detrimental effect of the action task on participants’ conceptual beliefs. For instance, with respect to balls varying in mass but not volume, whereas 61% of participants who did not perform the ball-dropping task correctly reported that a heavy ball would hit the ground before a light ball after being dropped simultaneously, only 42% of those who did complete the action task responded correctly, $\chi^2(1, N = 155) = 4.91$, $p = .03$. No significant differences in responding were found for the questions asking which ball is more affected by air resistance, $\chi^2(1, N = 155) = 0.06$, $p = .81$, and which ball is more affected by gravity, $\chi^2(1, N = 155) = 0.08$, $p = .93$. With respect to balls varying in volume but not mass, a comparable (though not significantly) lower percentage of participants who completed the action task (4%) correctly responded that a small ball would hit the ground before a large ball after being dropped simultaneously, $\chi^2(1, N = 155) = 0.28$, $p = .60$. In regard to the differential effects of air resistance, whereas 86% of participants who did not perform the ball-dropping task correctly reported that a large ball is more affected by air resistance than is an identically weighted small ball, only 66% of those who did complete the action task responded correctly, $\chi^2(1, N = 155) = 9.04$, $p < .01$. No significant difference in responding was found for the question asking which ball is more affected by gravity, $\chi^2(1, N = 155) = 1.94$, $p = .81$.

Discussion

In summary, the results of this experiment were fairly consistent with Experiment 1 in that there seemed to be two groups of people. The first group included participants who correctly believed that objects fall at different rates of acceleration depending on variations in volume and mass. These participants, who were in the minority, tended to drop the large ball before the small ball (of equal mass) and to drop the light ball before the heavy ball (of equal volume). The second group included participants who held a Galileo bias, believing that all objects fall at the same rate. These participants tended to drop the balls of all pairs at approximately the same time. However, for those reporting intentions of dropping both balls at the same time, the differences between release points were significantly greater than 0 ms. For the balls varying in volume but not mass, these participants dropped the large ball a mean of 17.43 ms before the small ball, and for the balls varying in mass but not volume, they dropped the light ball a mean of 24.40 ms before the heavy ball. These findings suggest that although action planning based on conceptual beliefs was generally evident, an accurate perceptual-motor knowledge also played a role in the execution of the actions.

An unexpected finding was the lack of improvement (or even a decrement in performance in some cases) with visual feedback across trials, despite the fact that a pilot study revealed that the visual feedback is sufficient to see that the balls fall at different rates. This surprising finding may be due to the complexity of the task—to the difficulty in determining the independent and combined effects of volume and mass on the rate of freefall. For instance, in regard to variations in volume, for the balls that were identical in mass (i.e., different in density), the large ball should have been released 100 ms before the small ball; however, for the balls that were different in mass (i.e., equal in density), the small ball should have been released 33 ms before the large ball. In regard to variations in mass, for the balls that were identical in volume (i.e., different in density), the heavy ball should have been released 200 ms before the light ball; however, for the balls that were different in volume (i.e., equal in density), the heavy ball should have been released only 33 ms before the light ball. These differences appear to have led to much difficulty in determining the independent and combined effects of volume and mass on the rate of freefall. Most participants (from the entire sample) seemed to handle this complexity by adopting a single strategy for all ball pairs, and this strategy was in the direction of the naive Galileo bias. Consequently, on the postexperimental survey, a larger percentage of participants responded incorrectly on the freefall and air resistance questions, revealing a seemingly detrimental effect of visual feedback in this action task on people's conceptual beliefs.

On an interesting note, the size–weight illusion was not evident in people's actions. This illusion refers to the commonly observed inverse relationship between physical volume and perceived heaviness; for objects of a constant mass, as the level of physical volume increases, the magnitude of the perceptual reports for perceived heaviness decreases. Similarly, for a constant mass, larger objects are judged to be lighter than smaller ones (Oberle & Amazeen, 2003). In the present experiment, many participants did verbally report that the large ball felt lighter than the small one (for the ball pair of identical mass). One might expect that people would be even more likely to drop the large light ball before small heavy ball, but the mean difference in release points was smallest for this ball pair. The size–weight illusion is a tremendously robust phenomenon in people's verbal reports, but the findings of this experiment suggest that the illusion may not affect one's actions in these types of circumstances. This finding is consistent with findings that the dorsal stream may be less susceptible to geometric illusions than is the ventral stream (e.g., Aglioti, DeSouza, & Goodale, 1995; Glover, 2002).

Experiment 3

In Experiment 2, the lack of improvement across trials and the strengthening of the false Galileo bias may have been due to participants' inability to adjust to the complexity of the task. To test this possibility, Experiment 3 used a simpler task, with the following variations. First, the physical differences in mass and volume were varied in four discrete steps, such that four levels of each were used. The differences in mass ranged from 0 kg (control) to over 4 kg, and the differences in diameter ranged from 0 cm (control) to over 35 cm. Second, the two highest levels of both the mass and volume differences were much greater than were the differences employed in Experiment 2. Third, the trials for the stimulus pairs varying in volume and for the stimulus pairs varying in mass were completed in separate blocks. Finally, the equal-density stimulus pair was eliminated. All of these changes were expected to allow participants to more easily determine the independent effects of volume and mass on the relative rates of freefall.

Method

Participants. Participants included 24 female and 24 male students enrolled in an introductory psychology course at Arizona State University. Age ranged from 18 to 27 years (M = 18.85, SD = 1.46). Of these participants, 17 had taken no physics courses, 29 had taken at least one high school physics course but had not taken any college physics courses, and 2 had taken at least one college physics course. All participants were naive to the purpose of the experiment.

Materials. The stimuli included eight pairs of tennis-style balls. Each of the first four pairs included a standard ball that was 325.0 g with a diameter of 6.5 cm. The four comparison balls were also 325.0 g each, but they varied in volume (diameter = 6.5 cm [control], 12.6 cm, 23.9 cm, 45.2 cm). Each of the final four pairs included a standard ball that was 312.7 g with a diameter of 13.1 cm. The four comparison balls each had a diameter of 13.1 cm as well, but they varied in mass (312.7 g [control], 1,087.5 g, 2,115.0 g, 4,647.6 g). Mass was varied independently of volume by filling the balls with a combination of plastic and lead weights, with care taken to distribute these materials evenly throughout the balls. In addition, the survey from Experiment 1 was administered (see Appendix).

Procedure. Participants completed 20 trials: 1 for each of the control stimulus pairs that were identical in both volume and mass and 3 for each of the experimental stimulus pairs that varied in either volume or mass. Half of the participants first completed the block of 10 trials composing the mass manipulation condition, followed by the block of 10 trials composing the volume manipulation condition. This general order was reversed for the other half of the participants. The presentation order of the stimulus pairs within each block of trials was counterbalanced across participants. The remainder of the procedure was identical to that of Experiment 2.

Results

The dependent variable recorded on each trial was the time between the two release points. For the control trials with the balls that were identical in both volume and mass, this time difference was only 3.13 ms (SD = 1.07 ms). Thus, we may consider 3 ms to be an approximate measure of random variation within trials. To assess performance on experimental trials, we analyzed the data via two mixed-design analyses of variance, with interstimulus differences (i.e., variations in volume or mass) and trial as the within-subject variables and sex and physics instruction as the between-subjects variables. In addition, a series of multinomial logistic regression tests were used to determine whether participants' actions and the visual feedback they received were beneficial to their conceptual knowledge assessed through the survey questions at the conclusion of the experiment. Because of the numerous tests, to correct for alpha inflation, we selected an alpha level of .01.

Ball pairs varying only in volume. Overall, participants correctly dropped the larger balls before the smaller standard ball (M = 49.65 ms, SD = 12.20 ms), and these time differences significantly increased as the differences in physical volume increased, $F(2, 88) = 14.48$, $p < .01$. However, the mean time differences for each variation in volume were closer to 0 ms than to the correct time between release points (see the top panel of Figure 3), again reflecting a strong Galileo bias. There were no significant effects of trial, $F(2, 88) = 0.37$, $p = .69$; physics instruction, $F(2, 43) = 1.04$, $p = .36$; or sex, $F(1, 43) = 3.72$, $p = .06$. Furthermore, none of the interactions among factors reached significance.

Ball pairs varying only in mass. Overall, participants correctly dropped the lighter standard ball before the heavier balls (M = 68.97 ms, SD = 16.05 ms), and these time differences significantly increased as the differences in physical mass increased, $F(2, 88) = 4.52$, $p = .01$. However, the mean time differences for each variation in mass were still less than the correct time between release points, and these time differences significantly decreased across trials, $F(2, 88) = 9.25$, $p < .01$ (see the bottom panel of Figure 3), again reflecting the influence of the Galileo bias on people's actions. There were no significant effects of physics instruction, $F(2, 43) = 1.59$, $p = .22$, or sex, $F(1, 43) = 4.59$, $p = .04$, and none of the interactions among factors reached significance.

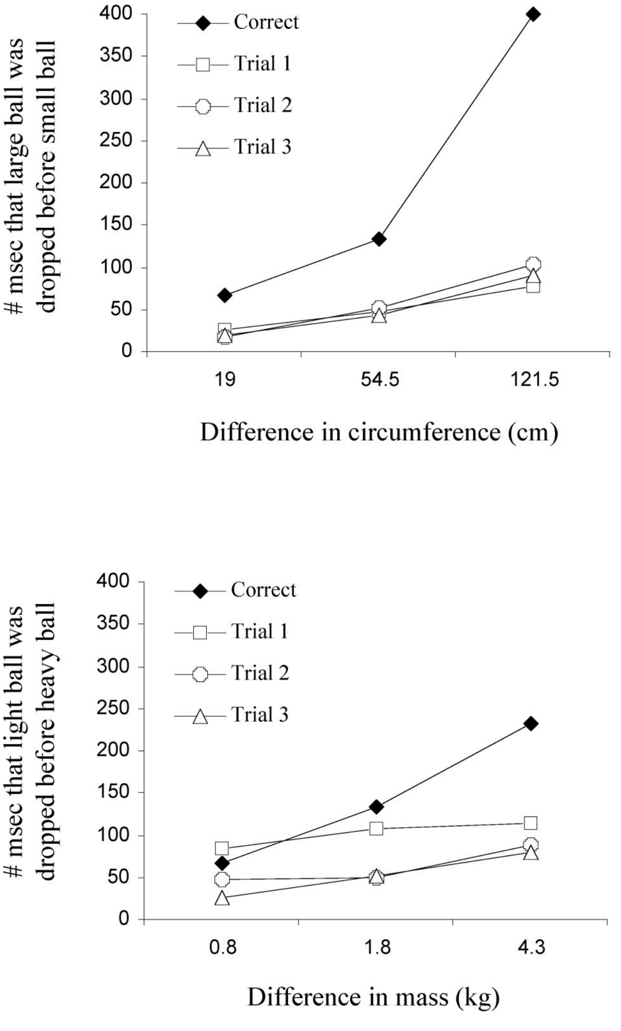

Figure 3. Results of Experiment 3. Mean differences in release times for the equal mass–different volume ball pairs (top panel) and the equal volume–different mass ball pairs (bottom panel) as a function of trial and variation in volume or mass.

Postexperimental survey responses. Comparison of the responses on the postexperimental survey questions with the responses given by the 105 control participants in Experiment 1 (no action task) generally revealed no effect of the action task on participants' conceptual beliefs. For instance, with respect to balls varying in volume but not mass, a statistically equivalent percentage of participants who completed the action task (38%) and participants who did not complete the action task (34%) correctly responded that a small ball would hit the ground before a large ball after both were dropped simultaneously, $\chi^2(1, N = 153) = 0.15$, $p = .70$. No significant differences in responding were found for the questions asking which ball is more affected by air resistance, $\chi^2(1, N = 153) = 0.15$, $p = .70$, and which ball is more affected by gravity, $\chi^2(1, N = 153) = 0.49$, $p = .49$. With respect to balls varying in mass but not volume, a significantly smaller percentage of participants who completed the action task (33%) compared with those who did not complete the action task (61%) correctly reported that a heavy ball would hit the ground before a light ball after being dropped simultaneously, $\chi^2(1, N = 153) = 10.02$, $p < .01$. No significant differences in responding were found for the questions asking which ball is more affected by air resistance, $\chi^2(1, N = 153) = 0.58$, $p = .48$, and which ball is more affected by gravity, $\chi^2(1, N = 153) = 0.02$, $p = .90$.

Discussion

Overall, these results are remarkably similar to those of Experiment 2. The majority of participants exhibited a Galileo bias in their actions, dropping both balls of each pair at approximately the same time. Less than 20% of participants consistently dropped the large ball before the small ball and the light ball before the heavy ball. Furthermore, for the other participants, performance seldom improved across trials; in fact, performance even declined in some cases. Thus, even in the simpler and more rapid task using balls with more pronounced differences in volume and mass, participants' actions were guided by the Galileo bias.

General Discussion

The present research shows that many people hold a relatively strong Galileo bias, believing that all objects fall at the same rate. The fact that our naive physics beliefs resemble those promoted by individuals hundreds of years earlier is not a new finding. For example, as McCloskey and others have pointed out, many people have adopted a naive belief in curvilinear impetus, which resembles theories introduced in the Middle Ages (Halloun & Hestenes, 1985a; McCloskey et al., 1980; McCloskey & Kargon, 1988). These researchers argue that, although the basic premises of these "common sense" beliefs are often very similar to misconceptions formalized by scientists in the past, one must not assume that the reason for these beliefs is because the individuals holding them today are familiar with the theories of the past. Rather, just as philosophers like Aristotle and the medieval impetus theorists developed certain physical understandings based on experience, so do individuals in modern times. The primary difference between the two groups is that the scientists and philosophers typically develop much stronger and more logically consistent arguments to support their beliefs, whereas the latter group's arguments are usually based on misunderstandings of concepts and physical illusions (see diSessa, 1988, for a review of the various bases of our naive physics beliefs).

For the present research, however, we cannot be so sure of the reasoning for people's naive Galileo biases. On one hand, most of our experiences with falling objects involve freefall from relatively short heights, at which the differences in the rates of freefall are usually imperceptible. So, for many people, this bias may indeed stem from everyday experiences. On the other hand, results of Experiment 1 revealed a detrimental effect of formal physics instruction on participants' beliefs. This result contradicts previous research that found a beneficial effect of physics instruction on people's beliefs about object motion (e.g., Donley & Ashcraft, 1992; McCloskey et al., 1980). Perhaps this negative effect may be explained by the lack of teaching emphasis on the effects of air resistance, a force with which we all have experience. For example, as mentioned previously, on the majority of the questions on two of the most comprehensive tests of people's beliefs about object motion and physical mechanics (Halloun & Hestenes, 1985b; Hestenes, Wells, & Swackhamer, 1992), students are instructed to ignore air resistance. To enhance accurate learning, instructors may need to use a combination of lectures and demonstrations that are consistent with both correct abstract equations from Newtonian mechanics and other factors, such as air resistance, that play a role in natural motion.

Another major finding in the present research is in regard to the influence of both our conceptual beliefs and an unconscious perceptual-motor knowledge on our actions. The majority of the participants in Experiment 2 indicated that they expected all the balls to fall at the same rate and that they subsequently intended to drop the balls of each pair at the same time. Compared with the other participants, these people did, in fact, drop the balls closer to the same time, implying that their naive conceptual beliefs (i.e., the Galileo bias) guided their actions. Nevertheless, they consistently dropped the light ball slightly before the heavy ball of identical volume, and they consistently dropped the large ball slightly before the small ball of identical mass, suggesting that an accurate perceptual-motor knowledge played a role in the execution of their actions.

In the literature, an increasing level of emphasis has been placed on the fact that at least two distinct forms of knowledge exist. Norman (1983) argued that people's mental models—their knowledge systems—involve not only a conscious form of knowledge that may be expressed in words and tested via written or verbal means but also an unconscious form of knowledge expressed in one's actions. Support for this declarative versus procedural knowledge distinction may be in found in Piaget's (1976) work, which shows the lack of cognizance of our successful actions. For example, Piaget had children swing a ball (by a string) above their head and release it so that the ball goes into a box directly opposite the child. In this task, most children performed fairly accurately, correctly releasing the ball before it "hit" the sagital plane; however, when asked when the ball should be released, most children falsely indicated that it should be released when it is directly in between the child and the box. A more practical example of such a dissociation between declarative and procedural knowledge is the predominantly used declarative knowledge used by people learning to drive, versus the predominantly used procedural knowledge used by skilled drivers.

Because a large part of our knowledge base arises from our visual experiences, we may relate the two knowledge systems to the two physiologically and behaviorally separate visual systems (for a review of these two systems, see Goodale & Haffenden, 1998; Milner & Goodale, 1995). Here, the ventral stream in the brain, which is responsible for visual perception and is associated with a verbal report of awareness, appears comparable to the conscious declarative knowledge system. Similarly, the dorsal stream, which is responsible for the visual guidance of one's actions, appears comparable to the unconscious procedural knowledge system. Furthermore, the two knowledge systems may be related to two separate action systems. Krist, Fieberg, and Wilkening (1993), for example, argued that the following two action systems exist: one involving conscious planning based on conceptual beliefs (for examples of actions guided by false beliefs, see McCloskey & Kohl, 1983; McCloskey, Washburn, & Felch, 1983) and the other involving perceptual-motor skills based on the perception of abstract physical relations. As suggested above and from the apparent lack of a size–weight illusion in the ball-dropping motor task, the current research provides further support for this interaction between cognition and perception-action systems—for the correspondence between the two knowledge systems, the two visual systems, and the two action systems.

Finally, this research revealed an unexpected lack of improvement with visual feedback. The exception to this finding was with the equal-density ball pair, in which most participants initially dropped the small, light ball too soon, a phenomenon we term an *Aristotle bias*. Many participants reported being fairly shocked that the "heavy ball did not catch up to the light ball." On the basis of the visual feedback, they came to the conclusion that the two fall at the same rate, and they subsequently dropped the two closer to the same time (correct time difference = 33 ms), resulting in improvement across trials. From these trials, participants may have adopted two heuristics: one assuming that heavy objects fall at the same rate as light objects and the other assuming that large objects fall at the same rate as small objects; the Galileo bias consists of both heuristics. This possibility would not be surprising, considering the fact that previous naive physics research has shown that people often have difficulty integrating multiple dimensions in relation to object motion (e.g., Donley & Ashcraft, 1992; Krist et al., 1993; Proffitt & Gilden, 1989). So, if one were to apply these two heuristics to the remaining two ball pairs, a lack of improvement (or even a decrement in performance) across trials would be expected; and the experimental results show just that. Despite the fact that a pilot study revealed that the visual feedback was sufficient to see that the balls fall at different rates, the complexity of the task in Experiment 2 (i.e., the difficulty in determining the independent and combined effects of volume and mass on the rate of freefall) and possibly the increased delay between trials led participants to adopt a single strategy for all ball pairs, and this strategy was in the direction of the naive Galileo bias. Yet, the majority of participants in Experiment 3, which employed a simpler and shorter task, also exhibited a Galileo bias in their actions with all ball pairs.

To further account for this finding, we believe that the differences in drop times were large enough to be perceptible but not large enough to be accepted as true or significant in light of participants' Galileo bias. This conclusion is consistent with Schauble's (1996) research assessing the effects of experimentation on children's beliefs in two physical science domains. In one of these domains, children were to perform experiments to determine which factors affect the speed of a boat being pulled in a canal. On a given trial, children first selected boats that were either rectangular, circular, or diamond in shape; they then had the option of loading the boat with a weight; and finally, they could choose to move the portable floor of the model canal to vary the depth of the water. For each trial, the children recorded the time that it took the boat to travel the length of the canal. Schauble found that in cases of small discrepancies between measurements on different trials, when the exact results were consistent with the children's beliefs, the measurement differences were accepted as valid. However, when the exact results were inconsistent with the children's beliefs, the discrepancies were attributed to measurement error. In relation to the current research, participants may have noticed the differences in drop times but felt that these differences were not large enough to be considered as representing a true effect and to justify changing their preconceived Galileo bias. Thus, to properly correct individuals' Galileo biases, perhaps instructors should employ alternative demonstrations such as objects falling in a medium with greater resistance, such as water. Nevertheless, the current research provides a nice illustration of the interaction between cognition and perception-action systems.

Air resistance is a force with which we all have experiences and which has a major impact in certain applied situations, such as baseball (e.g., Chambers, Page, & Zaidins, 2003; McBeath, 1990) and cycling (e.g., Swain, 1997). First, Coors Field, home of the Colorado Rockies, is widely known as a hitter's ballpark. At the high altitude of this stadium (5,280 ft above sea level), the air is significantly less dense than at other ballparks, resulting in a significantly lesser effect of air resistance on fly balls. In fact, despite the above-average size of the field, Coors Field led all major league ballparks in both number of homeruns hit and homeruns per at bat (by the home and visiting teams combined) for seven of its first eight seasons (Chambers et al., 2003). In addition, fly balls that do not make it over the fence fly approximately 20 ft farther at Coors Field compared with other ballparks. A second sport in which air resistance has a great impact is bicycle racing. Le Tour de France and other competitive bicycle races are actually team events (Swain, 1997). The start of the race is characterized by riding in a large pack called a *peloton*, in which only the riders at the head of the pack experience the full effects of wind resistance and the other riders save energy through drafting (i.e., by riding behind others, the riders experience only limited effects of wind resistance). As the pack begins to break, individual team members stay together and alternate positions in a pace line called an *echelon*, to conserve their energy while maintaining a competitive pace. As evidenced in these examples, air resistance clearly has an important practical impact on fast motion tasks, and an accurate conceptual knowledge can help people plan ahead to improve performance.

In conclusion, the present research elucidates a new category of naive physics, which we call the Galileo bias. This Galileo bias is the tendency for people to ignore the effects of air resistance and to assume that all objects fall at the same rate. When the physical dimensions of the objects differ by relatively small amounts, this conceptual bias becomes more pronounced and heavily influences people's actions on a ball-dropping task. Yet, for participants reporting intentions of dropping both balls at the same time, the differences between release points were significantly greater than 0 ms. These findings provide further support for theories of separate but interacting knowledge systems (e.g., Norman, 1983) and action systems (Krist et al., 1993). Future research must examine the generalizability of this bias by testing both adults and children on their beliefs and actions with objects varying in other characteristics such as shape and surface structure. We predict that the Galileo bias will be revealed in these extensions, as the current research suggests that the bias seems to be a fairly robust misconception.

References

Aglioti, S., DeSouza, J. F. X., & Goodale, M. A. (1995). Size-contrast illusions deceive the eye but not the hand. *Current Biology, 5,* 679–685.

Chambers, F., Page, B., & Zaidins, C. (2003). Atmosphere, weather, and baseball: How much farther do baseballs really fly at Denver's Coors Field? *The Professional Geographer, 55,* 491–504.

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. *American Journal of Physics, 48,* 1074–1079.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. Pufall (Eds.), *Constructivism in the computer age* (pp. 49–70). Hillsdale, NJ: Erlbaum.

Donley, R. D., & Ashcraft, M. H. (1992). The methodology of testing naive beliefs in the physics classroom. *Memory & Cognition, 20,* 381–391.

Galilei, G. (1974). *Two new sciences* (S. Drake, Trans.). Madison: University of Wisconsin Press. (Original work published 1638)

Glover, S. (2002). Visual illusions affect planning but not control. *Trends in Cognitive Sciences, 6,* 288–292.

Goodale, M. A., & Haffenden, A. (1998). Frames of reference for perception and action in the human visual system. *Neuroscience & Biobehavioral Reviews, 22,* 161–172.

Greenwood, M. S., Hanna, C., & Milton, J. (1986). Air resistance acting on a sphere: Numerical analysis, strobe photographs, and videotapes. *The Physics Teacher, 24,* 153–159.

Halloun, I. A., & Hestenes, D. (1985a). Common-sense concepts about motion. *American Journal of Physics, 53,* 1056–1065.

Halloun, I. A., & Hestenes, D. (1985b). The initial knowledge state of college physics students. *American Journal of Physics, 53,* 1043–1055.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force Concept Inventory. *The Physics Teacher, 30,* 141–158.

Hubbard, T. L. (1995). Cognitive representation of motion: Evidence for friction and gravity analogues. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 241–254.

Hubbard, T. L. (1997). Target size and displacement along the axis of implied gravitational attraction: Effects of implied weight and evidence of representational gravity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 1484–1493.

Kozhevnikov, M., & Hegarty, M. (2001). Impetus beliefs as default heuristics: Dissociation between explicit and implicit knowledge about motion. *Psychonomic Bulletin & Review, 8,* 439–453.

Krist, H., Fieberg, E. L., & Wilkening, F. (1993). Intuitive physics in action and judgment: The development of knowledge about projectile motion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 952–966.

Masin, S. C., & Crestoni, L. (1988). Experimental demonstration of the sensory basis of the size-weight illusion. *Perception & Psychophysics, 44,* 309–312.

McBeath, M. K. (1990). The rising fastball: Baseball's impossible pitch. *Perception, 19,* 545–552.

McCloskey, M., Caramazza, A., & Green, B. (1980, December 5). Curvilinear motion in the absence of external forces: Naïve beliefs about the motion of objects. *Science, 210,* 1139–1141.

McCloskey, M., & Kargon, R. (1988). The meaning and use of historical models in the study of intuitive physics. In S. Strauss (Ed.), *Ontogeny, phylogeny, and historical development* (pp. 49–67). Norwood, NJ: Ablex.

McCloskey, M., & Kohl, D. (1983). Naive physics: The curvilinear impetus principle and its role in interactions with moving objects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 146–156.

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive physics: The straight-down belief and its origin. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 636–649.

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action.* New York: Oxford.

Norman, D. A. (1983). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 7–14). Hillsdale, NJ: Erlbaum.

Oberle, C. D., & Amazeen, E. L. (2003). Independence and separability of volume and mass in the size-weight illusion. *Perception and Psychophysics, 65,* 831–843.

Pagonis, V., Guerra, D., Chauduri, S., Hornbecker, B., & Smith, N. (1997). Effects of air resistance. *The Physics Teacher, 35,* 364–368.

Piaget, J. (1976). *The grasp of consciousness* (S. Wedgwood, Trans.). Cambridge, MA: Harvard University Press. (Original work published 1974)

Proffitt, D. R., & Gilden, D. L. (1989). Understanding natural dynamics. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 384–393.

Schauble, L. (1996). The development of scientific reasoning in knowledge-rich contexts. *Developmental Psychology, 32,* 102–119.

Swain, D. P. (1997). A model for optimizing cycling performance by varying power on hills and in wind. *Medicine and Science in Sports and Exercise, 29,* 1104–1108.

Takahashi, K., & Tompson, D. (1999). Measuring air resistance in a computerized laboratory. *American Journal of Physics, 67,* 709–711.

Weichman, F. L., & Larochelle, B. (1987). Air resistance. *The Physics Teacher, 25,* 505–507.

Whitaker, R. J. (1983). Aristotle is not dead: Student understanding of trajectory motion. *American Journal of Physics, 51,* 352–357.

Appendix

Survey Questions Assessing Knowledge of Forces Acting on Objects in Freefall

1. If a small ball and a large ball (that weigh the same) are dropped from the top of the psychology building, which ball will hit the ground first?
   a) The small ball will hit the ground before the large ball. *(correct)*
   b) Both balls will hit the ground at the same time.
   c) The large ball will hit the ground before the small ball.
2. If a light ball and a heavy ball (that are the same size) are dropped from the top of the psychology building, which ball will hit the ground first?
   a) The light ball will hit the ground before the heavy ball.
   b) Both balls will hit the ground at the same time.
   c) The heavy ball will hit the ground before the light ball. *(correct)*
3. Of a small ball and a large ball (that weigh the same), which ball is the most affected by air resistance?
   a) The small ball is more affected by air resistance than the large ball is.
   b) Air resistance affects them equally.
   c) The large ball is more affected by air resistance than the small ball is. *(correct)*
4. Of a light ball and a heavy ball (that are the same size), which ball is the most affected by air resistance?
   a) The light ball is more affected by air resistance than the heavy ball is. *(correct)*
   b) Air resistance affects them equally.
   c) The heavy ball is more affected by air resistance than the light ball is.
5. Of a small ball and a large ball (that weigh the same), which ball is the most affected by gravity?
   a) The small ball is more affected by gravity than the large ball is.
   b) Gravity affects them equally. *(correct)*
   c) The large ball is more affected by gravity than the small ball is.
6. Of a light ball and a heavy ball (that are the same size), which ball is the most affected by gravity?
   a) The light ball is more affected by gravity than the heavy ball is.
   b) Gravity affects them equally. *(correct)*
   c) The heavy ball is more affected by gravity than the light ball is.

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