# An Intuitive Physics Study on the Role of Mass in Horizontal Collisions

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**Abstract**

The participants in our experiment were asked to judge whether simulated horizontal collisions appeared to be "natural" or "unnatural". We manipulated the simulated materials and the velocity ratio of two colliding objects. The results revealed a fair degree of consistency between predictions of Newtonian mechanics and the participants' responses.

**Keywords:** Intuitive physics; Collisions; Visual perception of causality.

## Introduction

Collisions are mechanical events with which everyone should be quite familiar. As was pointed out by McCloskey (1983), one may expect that as a result of everyday experience people should have an intuitive grasp of the physical principles that govern mechanical events. However, researchers in intuitive physics have shown that this is not always the case[1].

Starting with the ground-breaking work of Albert Michotte (1963), collision events have been extensively explored by researchers in the field of the visual perception of causality. Michotte and his followers typically focused on the genuine visual impressions elicited by collision events, employing experimental methods aimed at limiting the influence of cognitive factors on the participants' responses (see Choi & Scholl, 2006). Taking a different approach, researchers in the field of intuitive physics typically explored collision events using experimental methods that subtend both perceptual and cognitive processing of the stimulus information. This is consistent with the view that "Intuitive physics is a blend of perception, cognition and action" (Anderson, 1983, p. 231).

Some scholars (e.g., Anderson, 1983) argue that the cognitive system can integrate multiple sources of stimulus information and thus, in principle, it can deal with multidimensional mechanical events such as collisions. In contrast, other scholars (e.g., Proffitt & Gilden, 1989) maintain that the cognitive system is inherently limited, and thus "people make judgments about natural object motions on the basis of only one parameter of information that is salient in the event" (p. 384); accordingly, people should have poor intuitive understanding of multidimensional mechanical events.

[1] It is worth mentioning here Bozzi's pioneristic work on the intuitive physics of pendulum motion (1958).

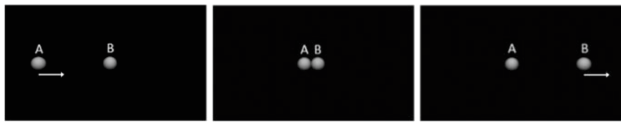


Figure 1: Three frames of a 3-D version of Michotte's stimuli. Letters *A* and *B* and arrows are added in this representation for references in the text and for indicating which object is moving in the two stages of the collision event. From Vicovaro and Burigana (2014)

### Overview of our contribution

In our study, we investigated the intuitive physics of collisions by determining the ranges of kinematic parameters that produced subjectively "natural" collisions in most trials. We used experimental stimuli with kinematic features similar to those of the stimuli employed by Michotte in his seminal work (which we call "simulated horizontal collisions", see Figure 1), and manipulated both the kinematic parameters and the implied masses of the colliding objects. Our aim was to explore participants' intuitive understanding of the relation between velocities and masses in horizontal collisions. In the experiment reported here we varied the implied masses of the colliding objects by manipulating their simulated materials[2].

## Physics of horizontal collisions

According to Newtonian mechanics, the relation between masses and velocities in horizontal collisions (see Figure 1) is defined by the following equation:

$$v_A/v_B = (1 + m_B/m_A)/(1 + e) \qquad (1)$$

where $v_A$ is the precollision velocity of object *A*, $v_B$ is the postcollision velocity of object *B*, $m_A$ and $m_B$ are the masses of objects *A* and *B* respectively, and *e* is the coefficient of restitution.

Figure 2 shows a graphic representation of Equation 1 when $e = 0.5$, $1 \leq m_A \leq 5$, and $1 \leq m_B \leq 5$. Two important properties of the resulting surface are worthy of note. One is that $v_A/v_B$ increases with $m_B$ and decreases with $m_A$, implying that, overall, $v_A/v_B$ increases as $m_B/m_A$ increases. We shall refer to this property as the "opposite monotonicity" of Equation 1. The other important property is that, for any fixed $m_A$, when $m_B$ diverges to infinity, $v_A/v_B$ also diverges to infinity, whereas when $m_B$ converges to zero then $v_A/v_B$ converges to $1/(1 + e)$. In other words, when the mass of *B* becomes infinitely large compared with the

[2] This experiment is part of a broader study which is described in Vicovaro and Burigana (2014).

mass of $A$, the postcollision velocity of $B$ becomes infinitely small compared with the precollision velocity of $A$. Conversely, when the mass of $B$ becomes infinitely small compared with the mass of $A$, the postcollision velocity of $B$ tends to be $1 + e$ times as large as the precollision velocity of $A$. All this implies that gradients of variation of $v_A/v_B$ as a function of $m_A$ and $m_B$ are greater when $m_A < m_B$ (the upper-left half of the surface) than when $m_A > m_B$ (the lower-right half of the surface). We shall refer to this property as the "gradient asymmetry" of Equation 1.

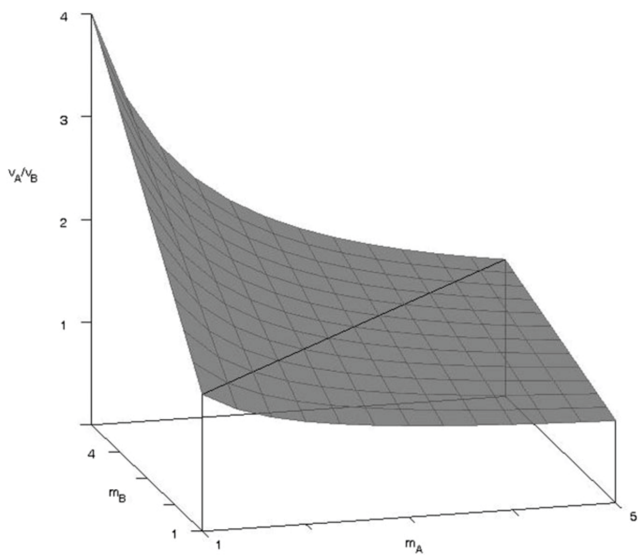


Figure 2: Graphical representation of the surface defined by Equation 1 for $e = 0.5$, $1 \leq m_A \leq 5$, and $1 \leq m_B \leq 5$. From Vicovaro and Burigana (2014).

## Experiment

The results of an experiment conducted by Natsoulas (1961) suggest that when participants are presented with simulated horizontal collisions such as those depicted in Figure 1, different impressions may occur depending on the velocity ratio $v_A/v_B$. When this ratio is close to 1, participants tend to have the impression of a "natural" physically plausible collision. In other words, the "reaction" of $B$ (i.e., its postcollision velocity) is judged to be adequate with respect to the "action" of $A$ (i.e., the precollision velocity of $A$). When $v_A/v_B$ is greater than 2, the prevalent impression is that of an "unnatural" collision, in which the postcollision motion of $B$ is braked by some resistance, rather than exclusively generated by the impulse from $A$. When $v_A/v_B$ is smaller than 0.5, the prevalent impression is that of an "unnatural" collision, but in this case the "reaction" of $B$ is judged to be exceeding the "action" of $A$—that is, the participants have the impression that the postcollision motion of $B$ is accelerated by an additional force rather than exclusively generated by the impulse from $A$.

Based on these insights, in the present study we define the *upper naturalness bound* as the value of the ratio $v_A/v_B$ above which more than 50% of the time participants judge the motion of $B$ to be "unnatural" (presumably because it seems "braked" by some external force). We define the *lower naturalness bound* as the value of the ratio $v_A/v_B$ below which more than 50% of the time participants judge the motion of $B$ to be "unnatural" (presumably because it seems "accelerated" by some external force). Finally, we define the *naturalness interval* as the interval of $v_A/v_B$ values that lie between the two bounds and that give rise to the impression of a "natural" collision more than 50% of the time.

We varied the implied masses of $A$ and $B$ through manipulations of their simulated materials. We first estimated, for each combination of implied masses of Objects $A$ and $B$ and for each participant, the individual upper and lower naturalness bounds by using the psychophysical method of "randomly interleaved staircases" (Levitt, 1971). Then, we determined each individual naturalness interval, which included the velocity ratios lying between the two bounds. Finally, we performed a statistical analysis on the midpoint of each individual naturalness interval, which was given by the arithmetic mean of each individual upper and lower bound. Midpoints provided relatively simple and reliable measures of how the experimental manipulations influenced the individual naturalness intervals.

In order to evaluate whether participants had good intuitive understanding of the relation between velocities and masses in collision events, we determined how the locations of the naturalness intervals varied along the $v_A/v_B$ continuum as a function of the implied masses of $A$ and $B$, and tested whether this reflected the two most salient features of Equation 1, i.e., "opposite monotonicity" and "gradient asymmetry" as represented graphically in Figure 2. Specifically, if the participants' responses are consistent with physics, then the naturalness intervals should shift downwards along the $v_A/v_B$ continuum as the implied mass of $A$ increases, and should shift upwards along the same continuum as the implied mass of $B$ increases (opposite monotonicity). Moreover, the location of the naturalness intervals on the $v_A/v_B$ continuum should vary more with the implied masses of $A$ and $B$ when the former is smaller than when the latter is smaller (gradient asymmetry). This would support the idea that the cognitive system can integrate multiple sources of stimulus information (Anderson, 1981, 1983), thus showing that it can deal (in principle) with multidimensional mechanical events.

### Method

**Participants:** Fifteen psychology students at the University of Padua (aged 19–27, four males) participated in the experiment. They all had normal or corrected-to-normal visual abilities, and were paid for their participation.

**Stimuli and apparatus:** The stimuli were presented on a personal computer equipped with a 37.5 cm × 30 cm CRT screen and a keyboard. Participants sat at a distance of about 50 cm from the screen, the background of which was black. Two simulated spheres of equal size were presented on the screen, at its middle height, with their centers aligned horizontally. Their apparent size, computed from the diameters of their corresponding images on the screen (2.55 cm), was 8.7 $cm^3$, subtending a visual angle of about 2.92°. At the beginning of each animation, one sphere (*A*) appeared close to the left edge of the screen and the other sphere (*B*) appeared in the center. Then, 170 ms after the appearance of the spheres, *A* began to move horizontally from left to right towards *B*, uniformly and without rotation, until it made contact with it. At this point, *A* came to a stop and *B* started moving in the same direction as *A* had been moving, uniformly and without rotation, until it stopped close to the right edge of the screen (see Figure 1). We manipulated the simulated materials of *A* and *B* according to a 3 Material *A* (polystyrene, wood, iron) × 3 Material *B* (polystyrene, wood, iron) factorial design. The spheres were created with 3D Studio Max™; photographic textures depicting the simulated materials were attached to their surfaces, and their reflectances were regulated in order to increase the realism of their appearance. The velocity of *A* was kept the same (15.5 cm $s^{-1}$) across the experiment. In each of the nine experimental conditions, we varied the velocity of *B* in order to determine the individual upper and lower naturalness bounds.

**Procedure:** Prior to the experiment, participants read and signed informed consent forms that had been approved by the local ethics committee (Department of General Psychology, University of Padua). Instructions that were readable on the screen informed the participants that they would be presented with two simulated colliding spheres, which could be made of any one of three different materials: polystyrene, wood, or iron. The participants were asked to pay attention to the postcollision velocity of the initially stationary sphere (*B*), and were informed that the initially moving sphere (*A*) would always be stationary after the collision. They were asked to judge whether the postcollision motion of sphere *B* was “natural” or “unnatural” compared with the force apparently exerted by the initially moving sphere (*A*). The instructions specified that “unnatural” could have two alternative meanings: first, that the motion of *B* was too slow compared with the force apparently exerted by *A*, as if the motion of *B* had been braked by some resistance; or, second, that the motion of *B* was too fast compared with the force apparently exerted by *A*, as if the motion of *B* had been accelerated by an additional force. In each trial the participants were allowed to view the stimulus as many times as they wanted by pressing the spacebar on the keyboard; when they felt ready to respond, they had to press “N” for the “natural” response, or “Z” for the “unnatural” one. After reading the instructions, the participants were presented with five randomly chosen stimuli to familiarize them with the task.

**Experimental design** In order to estimate the individual upper and lower naturalness bounds, we used the method of “randomly interleaved staircases”. In each of the nine experimental conditions, we varied the velocity of *B* (the velocity of *A* was fixed at 15.5 cm $s^{-1}$) such that the $v_A/v_B$ ratio could take on 21 possible values that ranged from 1/3 to 3. A full description of the experimental design can be found in Vicovaro and Burigana (2014).

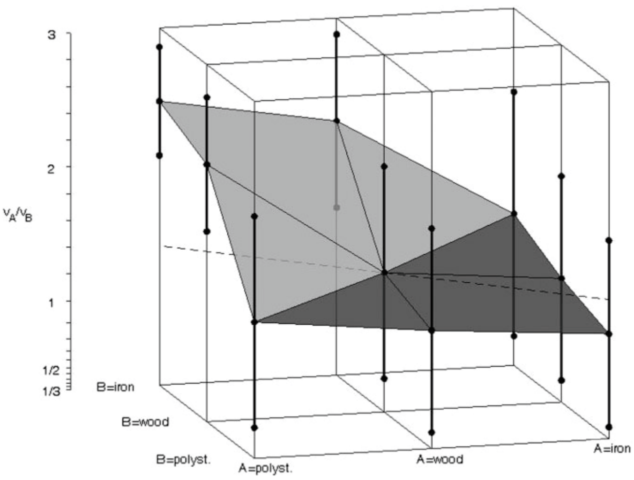


Figure 3: Mean naturalness intervals for each combination of simulated material of spheres *A* and *B*. Dark and light grey halves of the surface correspond to the experimental conditions in which the implied mass of *A* is greater and, respectively, smaller than the implied mass of *B*. The dashed line is the horizontal diagonal line through the midpoint of the central naturalness interval (*A* = wood and *B* = wood). From Vicovaro and Burigana (2014).

## Results and discussion

Figure 3 shows the naturalness intervals (averaged across participants) that were obtained in each of the nine conditions of the experiment. For each interval we mark three points: the mean upper naturalness bound (top of the interval), the mean lower naturalness bound (bottom of the interval), and the midpoint of the interval. Along the $v_A/v_B$ continuum, the naturalness intervals shift steadily downwards as the implied mass of sphere *A* increases, shift steadily upwards as the implied mass of sphere *B* increases, and vary more in the light grey half of the surface than they do in the dark grey half (the former corresponds to the experimental conditions in which the implied mass of *B* exceeded the implied mass of *A*). In other words, the locations of the naturalness intervals along the $v_A/v_B$ continuum appear consistent with the opposite monotonicity and gradient asymmetry properties of Equation 1 (see Figure 2 for a comparison).

In order to test this evidence statistically, we performed a two-way within-participants ANOVA (with factors material sphere *A* and material sphere *B*) on the midpoints of the naturalness intervals. For the properties of ANOVA, opposite monotonicity should result in significant main effects of the two factors, whereas gradient asymmetry should result in significant interaction effects. Indeed, the main effects of the two factors were significant, as $F_{2, 28}$ = 47.6, *MSE* = 6.25, $p < 0.001$, and $\eta_p^2 = .77$, and $F_{2, 28}$ = 44.94, *MSE* = 8.46, $p < 0.001$, and $\eta_p^2 = .76$, respectively. Their interaction effects were also significant, as $F_{4, 56}$ = 18.67, *MSE* = 1.39, $p < 0.001$, and $\eta_p^2 = .57$.

Significant interaction effects between the two experimental factors are necessary but not sufficient for confirming gradient asymmetry statistically. We reasoned that a reliable (although local) test of this condition may be obtained by comparing the following two measures: the difference between the midpoint corresponding to the back left corner of the surface in Figure 3 (*A* = polystyrene, *B* = iron) and the midpoint in the center of the surface (*A* = wood, *B* = wood), and the difference between the latter and the midpoint corresponding to the front right corner of the surface (*A* = iron, *B* = polystyrene). If the former difference is greater than the latter difference, then this would indicate that the surface is steeper in the light grey half than it is in the dark grey half. Both differences between midpoints were computed for each participant and were compared statistically by means of a paired-sample *t*-test, which showed that the former measure (*M* = 1.16, *SD* = 0.56) was higher than the latter measure (*M* = 0.28, *SD* = 0.21), $t(14) = 6.82$, $p < 0.001$, and Hedge's $g_{av} = 2.22$. This result confirms that the locations of the naturalness intervals along the $v_A/v_B$ continuum were (approximately) consistent with gradient asymmetry.

Overall, a comparison between Figure 3 and Figure 2 reveals important similarities between the locations of the naturalness intervals along the $v_A/v_B$ continuum and the expectations from Equation 1; both are characterized by opposite monotonicity and gradient asymmetry. Regarding these two properties, the former means that participants intuitively understand that $v_A/v_B$ increases with $m_A$ and decreases with $m_B$, whereas the latter means that they intuitively understand that $v_A/v_B$ varies more with $m_A$ and $m_B$ when $m_A<m_B$. This suggests that, when participants are required to judge the "naturalness" of the postcollision motion of *B*, they integrate the velocities and the implied masses of the colliding objects in a manner consistent with Equation 1.

Notably, the similarities between participants' responses and Equation 1 are not perfect in at least two respects. First, Figure 3 shows that the mean lower naturalness bounds in the dark grey half of the surface tend to be smaller than 0.5, whereas, according to Equation 1, $v_A/v_B$ cannot be smaller than this value (it is close to 0.5 when $m_A$ is very large, $m_B$ is very small, and $e = 1$). Second, the mean naturalness intervals include a wide range of $v_A/v_B$ values that have been judged "natural". We may speculate that this is due to the fact that the coefficient of restitution ($e$) was unknown, and, consequently, participants may implicitly have assumed that there were many $v_A/v_B$ values that were compatible with "natural" collisions. Or else this may simply reflect uncertainty in participants' response processes.

## Conclusions

In sum, the results of our study are consistent with the idea that people's intuitive judgments about collision events can be at least partially reconciled with Newtonian mechanics, as has been recently suggested by Sanborn, Mansinghka, and Griffiths (2013). This does not mean that people are aware of the Newtonian conceptualization of collision events; rather, it means that their intuitive judgments are *qualitatively consistent* with certain predictions from Newtonian equations.

Overall, our results suggest that people's "naturalness" judgments of the postcollision motion of Object *B* are based on the implied masses of both involved Objects *A* and *B* (in addition to the precollision velocity of *A*). This does not seem to support the claim that "people make judgments about natural object motions on the basis of only one parameter of information that is salient in the event" (Proffitt & Gilden, 1989, p. 384). On the contrary, our findings lend support to the idea that the cognitive system can integrate multiple sources of stimulus information (Anderson, 1983). In principle, this should enable people to understand multidimensional mechanical events, though misconceptions reported in the intuitive physics literature suggest that this skill is sometimes insufficient.

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