ARISTOTLE VERSUS PHILOPONUS: A FUNCTIONAL APPROACH TO THE INTUITIVE PHYSICS OF PROJECTILES

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Abstract

Intuitive physics is a popular field of research within cognitive psychology which addresses the common-sense beliefs about the physical world, particularly about classical mechanics. An influential stream of research argues for the striking resemblance between common-sense beliefs and those embodied in pre-Newtonian theories, such as the medieval physics of impetus. In this study, two early algebraic proposals for the relation between the force applied to an object, the resistance to its motion and its resulting velocity are compared, the first one derived from Aristotle, the other set forth by Philoponus (VIth century). The methodology of Information Integration Theory was used, revealing a dividing cognitive integration rule in agreement with Aristotle's proposal. The significance of this finding is discussed through a suggested link with the mental models framework.

Intuitive Physics has earned an honorable place within cognitive psychology (see McCloskey, 1983a). As a field of study, it addresses the spontaneous representations of the physical world, especially those concerning the phenomena described by classical mechanics. One advantage of intuitive physics regarding other domains of cognitive psychology is the possibility to assess the correctness of cognitive representations against a non arbitrary criterion, which is provided by Newtonian Mechanics (Anderson, 1981). This capability soon led to the finding of systematic and persistent (to the point of resisting formal instruction) divergences between our intuitions and the physical reality (Trowbridge & McDermott, 1980; Champagne, Klopfer & Anderson, 1980; Caramazza, McCloskey, & Green, 1981; Clement, 1982; McCloskey, 1983a; 1983b; diSessa, 1998). Examples of commonly diagnosed misconceptions include the "straight-down belief" for the path of an object dropped from a moving carrier, the assumption of a curvilinear impetus, or the notion that heavy bodies fall more rapidly than light bodies. Two major sorts of explanation have been proposed for these mistaken beliefs. One of them invokes the processing limits of our cognitive apparatus, particularly when it comes to the integration of multiple dimensions (Kayser, Proffit , & Anserson, 1985); in the version given by Proffit and Gilden (1989), accurate dynamic judgments can only be obtained for events so simple that one single category of information (dimension) is all that needs to be considered. The other emphasizes the non random character of these errors to defend their subsumption under coherent naïve theories of the physical world, bearing moreover epistemological parallels to pre-Newtonian views such as the medieval theory of impetus (McCloskey, 1983a) or Aristotelian physics (Champagne, Klopfer, L. & Anderson, 1980). Given the centrality of mechanics to both modern and ancient physics, discussion has largely been held around our intuitions of motion and, particularly, of the motion of projectiles.

The common trait to all pre-Newtonian theories of movement is that motion, differently from rest, requires a cause (which violates Newton's first law). Aristotle conceived of that cause as external, thus distinguishing between the moving body (the *motus*) and the agent of movement (the *movens*). This raised difficulties for understanding projectile motion after the separation from the launcher, leading Aristotle to conjecture a double role for the medium (typically, the air): "resistive" in the front of the *motus*, "motive" on its rear. Because no movement would be possible in the vacuum (where it would became infinite) the properties of motion would be determined by the relation between the applied motive force (*F*) and the resistive force opposed by the medium (*R*). From some qualitative remarks of Aristotle, seemingly suggesting a direct proportionally of velocity to F and its inverse proportionality to *R*, peripatetic scholars have later came to propose the following algebraic formulation (Jammer, 1957; Celeyrette, 2008):

$$Velocity = {}^{Force}/_{Resistance} \quad (1)$$

This formula had shortcomings that did not go unnoticed, like delivering a positive value (V=1) when F and R were absolutely commensurate. An alternative formulation was proposed by Philoponus (VIth century), who conceived of the cause of movement as a force internal to the moving object, its *impetus*. This general notion was later systematized by Jean Buridan (XIVth century) in what came to be known as the "impetus theory" of motion. In the case of a projectile, the *impetus* is imparted to it by a launcher/thrower and dissipates under the action of external forces like air resistance or friction. Philoponus rule expressed velocity as proportional to the excess of *F* over *R*, giving a "0" result when *F* = *R*.

$$Velocity = Force - Resistance \quad (2)$$

A third influential algebraic law was still provided by Bradwardine (XIVth century), which allowed both to overcome the flaw in the peripatetic formula and to avoid the (non-Aristotelian) implication of Philoponus rule that movement could happen in the vacuum (by making R = 0), writing in modern notation as (Clagett, 1957; Thakkar, 2007):

$$Velocity = log\left({}^{Force}/_{Resistance}\right) \quad (3)$$

From the standpoint of intuitive physics, these early algebraic formulations have the interest of shifting the debate between Aristotelian and medieval theories to the terrain of functional knowledge (concerning the functional relations among different, usually continuous, variables). Not only this allows more straightforward comparisons to modern mechanics, as it offers a distinctive path for investigating potential analogies with the functional structure of spontaneous representations. Because it has been instrumental in establishing the relevance of a "cognitive algebra" in several domains, Information Integration Theory (Anderson, 1981; 1982) appears as a natural framework to that endeavor. A typical integration task combines factorially a minimum of two independent variables and analyses the pattern of results arising from their integration into a continuous response dimension, which may or not be of a verbal nature. If the task happens to be one of intuitive physics, emerging integration rules can then be interpreted as the analogue of a "physical law", and the functional metrics derived for the factors as the analogue of the metric physical variables conjoined by the law (see Anderson, 1991).

In this study, "motive force" an "resistance of the medium" were rendered operational and manipulated as factors in an integration task with the twofold purpose of investigating the existence of consistent cognitive algebraic models in the domain and, in such eventuality, of comparing them to the peripatetic and medieval algebraic formulations.

Method

Participants

33 students (30F; 3M; Mean age 20.12 [4.86]) at the University of Coimbra, all unaware of the purpose of the experiment, participated in exchange for course credits

Stimuli

Schematic side views of a launching apparatus were used as stimuli (see figure 1). The apparatus consisted of a horizontal tube, filled with one of three colors that stood for different material fluids (resistive mediums): white for air, blue for water, yellow/brown for honey. A sphere was depicted inside the tube, which could be set into motion by the release of a spring mechanism displaying one of four possible degrees of tension (force). A dashed orthogonal line intersected the tube at one of three different distances from where the sphere was at rest.

Design and Procedure

The experiment obeyed a 4 (*force*) × 3 (*resistance*) × 3 (*distance*) full factorial repeated-measures design. Participants were required to provide estimates of the traveling velocity of the sphere when it reached the vertical line after the spring was released. Answers were given on a visual-analogue scale presented above the stimulus, with anchors *0-Sphere at Rest* and *20-Maximum velocity allowed by the launching device*. The experiment was run in a PC equipped with a flat LCD screen (located 60 cm ahead of the participants). Stimuli presentation and response collection were performed with SuperLab 4.0.

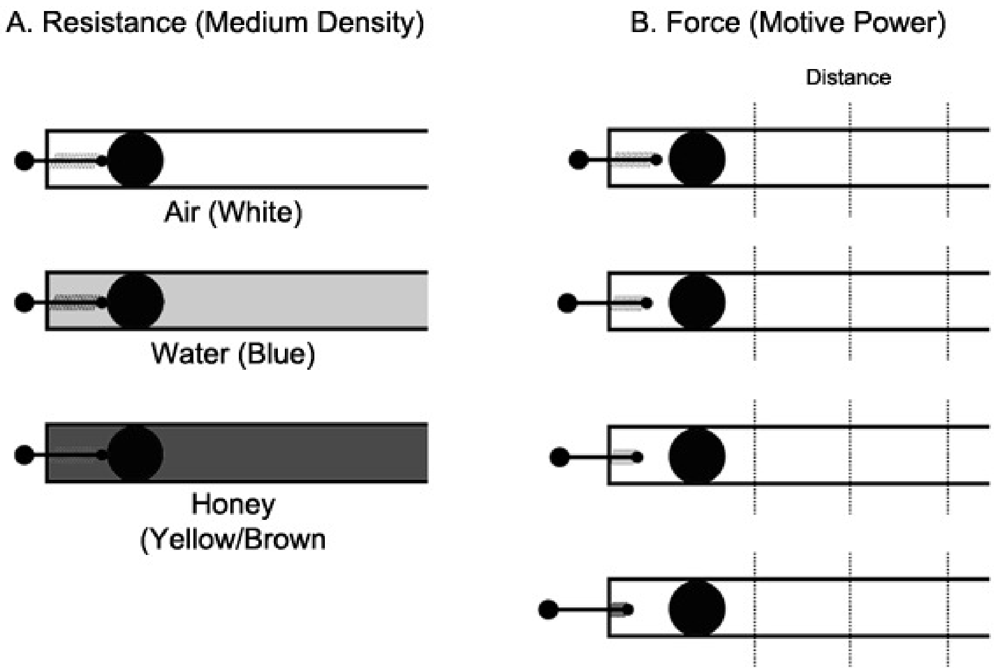

Figure 1 – Schematic representation of the stimuli set. Panel A: Variation of the implied density of the medium (resistance), conveyed through different colors. Panel B: Variation of the motive power (Force) impartable by the mechanism (suggested by 4 different length contractions of the spring), and of the distance traveled by the sphere along three levels (dashed lines).

Results

Figure 2 presents the factorial plots of *motive force* × *resistance of the medium* (with the former factor on the abscissa and the later as the curve parameter). Mean ratings of velocity on the ordinate are aggregated over the levels of the third factor (*distance traveled*). The positive slope of the lines is suggestive of an increasing effect of *force* on velocity estimates, while their vertical separation indicates an opposite diminishing effect of *resistance* (levels of resistance augment from top to bottom). A fan-like pattern is clearly apparent in the graph, with growing rightward divergence of the lines. Given that *resistance* operates decreasingly, this suggests that force and resistance combine divisibly in determining the judgments of velocity, which might write as $force \div resistance$, or equivalently as *force* × *1/resistance*. Statistical analysis fully supported the graphical analysis. A repeated-measures ANOVA performed over the velocity estimates revealed significant main effects of both factors, *Force*, $F(1.176, 37.628) = 46.173$, $p < 0.001$, *Resistance*, $F(1.436, 45.954) = 54.51$, $p < 0.001$, and a significant interaction among them, $F(3.519, 112.62) = 11.348$, $p < 0.00$, located moreover on the linear × linear component, $F(1,32) = 25.453$, $p = .000$. The proper statistical test of a multiplicative/divisive rule requires that (a) only the linear × linear component of the interaction is significant and that (b) no systematic residuals are left over the other components of the interaction term (Anderson, 1982). The first criterion was shown in the ANOVA to be met by our results. The second criterion was checked with the statistical package CALSTAT (Weiss, 2006), which showed no significant residuals left by the bilinear component ($F < 1$ for the residuals).

Data were further cluster analyzed (hierarchical clustering; complete linkage method; Squared-Euclidian metrics; standardized cases), which led to the finding of two subgroups of participants differing on the role played by *traveled distance*, the third factor in the design. In a major cluster of subjects (CL1; n = 21), *distance* had both a decreasing significant main effect, $F(1.107, 22.139) = 12.469$, $p < 0.01$, and a significant interaction with *motive force* $F(4.059, 81.177) = 3.829$, $p < 0.01$. Similarly to the interaction *force* × *resistance*, the bilinear component was the only one to reach significance and left no systematic residuals behind ($F < 1$). In Cluster 2 (CL2; n = 9), distance had no effects whatsoever. In both clusters, the pattern of results for the other factors, *force* and *resistance*, remained the same (both graphically and statistically) as in the overall analysis. No second order interactions were observed either in the overall ANOVA or in the ANOVAs addressing each cluster separately.

Considering all indications, a general algebraic dividing model between *force* and *resistance* appears well warranted in both CL 1 and CL 2, writing as:

$$Velocity = {}^{Motive\ Force}\!/_{Resistance\ of\ the\ Medium} \quad (4)$$

For participants in CL 1 (the vast majority), where *distance* has an effect, the model can be more fully specified to account for the similarly dividing relation between *force* and projectile's *traveled distance*, and for the additive relation between *traveled distance* and *resistance of the medium*, indicated by graphic parallelism and a null interaction term, hence writing now as:

$$Velocity = \frac{Motive\ Force}{Resistance\ of\ the\ Medium + Travelled\ Distance} \quad (5)$$

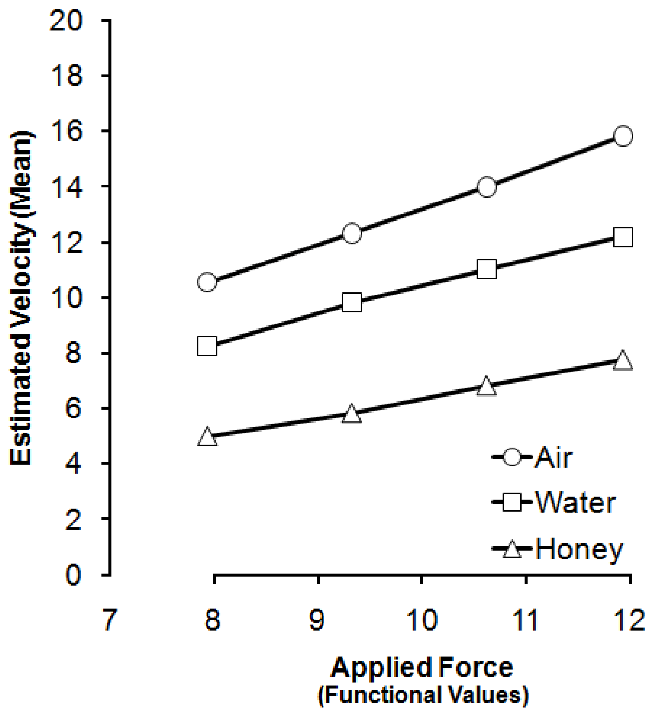

Figure 2 – Factorial plot of *Force* (on the abscissa) × *Resistance* (curve parameter), with mean estimates of velocity, aggregated over the levels of the factor distance, on the ordinate. Horizontal spacing on the abscissa is given in functional values, corresponding to the marginal means of *Force* (see Anderson, 1982, for the underlying rationale)

Discussion

Results consistently establish that a dividing integration rule between Motive Force and Resistance of the Medium underlies the subjective estimates of the velocity of projectiles. This agrees with the peripatetic algebraic rule V = F/R (velocity directly proportional to the force applied, and inversely proportional to the resistive force), and disagrees with the F - R rule advanced by Philoponus under the impetus theory (velocity proportional to the excess of motive force over resistance). However, this should not be too hastily taken as support for the Aristotelian character of naïve physics. On the one hand, extrapolating from a local functional model the entire "paradigm" of the Aristotelian physics of projectiles is, to say the least, problematic. To appreciate this, one might note that Bradwardine's formula, which was fully Aristotelian in spirit and sough only to improve on the peripatetic canon, is similarly disproved by our findings, given that $V = \log (F/R)$ is expressable as $V = \log F - \log R$, a subtractive rule just as the one advanced by Philoponus. On the other hand, the observed pattern of individual differences appears irreducible to either an Aristotelian or an impetus view. The lack of effects of *distance traveled* found in CL 2, for instance, is incompatible both with the impetus theory, which includes the dissipation of impetus as an explanatory piece, and with the Aristotelian physics, which requires the resistive force of the medium. As another example, a consistent subtractive operation of *motive force* was found in one subject left outside the clusters (which, given that attrition due to fluids was at stake, could be expressing the physically motivated notion that resistance opposed by a fluid to the motion of an objects increases with motion's velocity). Such cognitive models find no historical analogue in either of the pre-Newtonian paradigms, and should be more properly thought of as pre-paradigmatic.

On the whole, the divisive integration rule between *force* and *resistance* appears best interpretable as a prevalent “mental model” (rather than as the expression of a general naïve theory: see Gentner, 2002, and also diSessa, 1998) whereby subjects understand and infer some properties of the motion of projectiles. By showing the lawful joint operation of those two factors and indeed, for a majority of participants, of all three factors in the experiment (Eq. (5) above), these findings are at odds with the claim that everyday representations of dynamics rest firstly on a cognitive inability to handle multidetermination (Kaiser et al., 1985; Profitt & Gilden, 1989). Rather than lying outside the scope of application of cognitive algebra, intuitive physics might actually be one of its most congenial domains (see Anderson, 1981, 1996).

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