The way the ball bounces: visual and auditory perception of elasticity and control of the bounce pass

William H Warren Jr1, Elizabeth E Kim, Robin Husney
Department of Psychology, Brown University, Providence, RI 02912, USA
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Abstract. Human observers may perceive not only spatial and temporal dimensions of the environment, but also dynamic physical properties that are useful for the control of behavior. A study is presented in which visual and auditory perception of elasticity in bouncing objects, which was specified by kinematic (spatiotemporal) patterns of object motion, were examined. In experiment 1, observers could perceive the elasticity of a bouncing ball and were able to regulate the impulse applied to the ball in a bounce pass. In experiments 2 and 3, it was demonstrated that visual perception of elasticity was based on relative height information, when it was available, and on the duration of a single period under other conditions. Observers did not make effective use of velocity information. In experiment 4, visual and auditory period information were compared and equivalent performance in both modalities was found. The results are interpreted as support for the view that dynamic properties of environmental events are perceived by means of kinematic information.

1 Introduction

Visual perception of three-dimensional structure and motion has received much attention in the literature on psychology. But there are many other properties of the physical environment that are relevant to the control of behavior and might be advantageous for observers to perceive visually. Such properties include the weight, elasticity, and rigidity of objects, the hardness, slipperiness, and solidity of surfaces, the viscosity of fluids, and the forces acting on these bodies. In this study we examined one such property, the elasticity of bouncing objects, to determine whether it can be perceived visually and auditorily and used to regulate action, and to determine the optical and acoustical information upon which its perception is based.

What might be the basis for the perception of physical properties? Whereas some of them may be specified in a static image, others are more likely to be revealed by events, spatiotemporal transformations of objects that occur autonomously or are produced by an observer in the course of perceptual exploration (Warren and Shaw 1985). For example, the visible patterns of motion during an event such as a collision between two objects are influenced by the physical properties of the objects involved, such as mass, elasticity, and friction, and thus may reveal something about those properties. Many mechanical events have lawful consequences such as unique spatiotemporal patterns of reflected light or acoustic disturbances. If such patterns map one-to-one or many-to-one onto object properties, then they constitute optical or acoustical information that specifies those properties (Gibson 1966; 1979). To the extent that perceptual systems can detect such spatiotemporal patterns, an observer can perceive the environmental properties they specify.

The theoretical problem is that descriptions of optical and acoustical patterns are typically of a lower dimensionality than descriptions of environmental properties, so that there is no simple mapping of variables such as elasticity or force onto variables of the spatiotemporal structure of light and sound. For example, force can be dimensionally analyzed into variables of length, time, and mass (LT⁻²M), whereas spatiotemporal
changes in optical structure can only be analyzed into variables of length and time (for example, \(LT^{-1}\)). Runeson (1977a) proposed an approach to this problem for the class of dynamic physical properties, based on known relationships between the kinematics and dynamics of moving objects. Kinematics is the branch of mechanics that describes pure motion, employing the variables of displacement, time, velocity, acceleration, and so on; dynamics (or kinetics) is the branch of mechanics that analyzes such motions by taking into account the various forces that produce them, including the variables of mass, friction, elasticity, force, momentum, and so on. Runeson demonstrated that the relative mass and elasticity of two colliding objects are specified by their motions and hence by corresponding kinematic optical patterns, in short, that “kinematics specifies dynamics”. The existence of such kinematic information for dynamic properties can be determined analytically, and the ability of observers to detect it can be tested empirically.

Two lines of research have emerged from the recent interest in such physical properties: work in naive physics, which tests cognitive knowledge of principles of classical physics, and work in event perception, which tests perceptual judgments of physical and other environmental properties. In order to assess explicit physical concepts, research on naive physics has typically employed cognitive tasks such as word problems and diagrams, and often found surprising patterns of errors. For example, McClosky et al (1980) presented subjects with a diagram of a ball on a string being whirled in a circle and asked them to draw the path the ball would take if it were released; 36% of the subjects drew curved paths, when in fact a straight path tangent to the circle would occur. Similar systematic errors were obtained on several other problems: 51% drew curved paths for a ball shot out of a curved tube, and 60% drew nonparabolic paths for a ball dropped from a moving airplane (McClosky 1983). The experimenters concluded that many subjects hold a naive ‘impetus’ theory of motion analogous to medieval physics, which mediates their performance in everyday encounters with moving objects (McClosky 1983; McClosky and Kohl 1983). This conclusion is puzzling given that people appear able to act successfully and survive in a world governed (to a close approximation) by Newtonian, not medieval, mechanics. If humans behaved in accordance with a naive impetus theory, outfielders would routinely miss fly balls and David would have perished at the hands of Goliath.

In contrast, the literature on event perception typically reports reasonably accurate perceptual judgments of physical properties when observers are presented with displays of ongoing events and are asked to judge what they see. For example, when viewing filmed-event versions of the curved-tube problem, subjects were much more accurate in judging the correctness of the trajectory of a ball than they were with static diagrams (Kaiser et al 1985). Following the work of Michotte (1946/1963) and Runeson (1977a) on the perception of causality and dynamics, we presented computer-generated displays of two colliding objects and asked adults to judge which object looked heavier (Todd and Warren 1982). These relative mass judgments were accurate under most conditions, except at extreme values of elasticity or velocity. Kaiser and Proffitt (1984) found that even children as young as 5 years of age performed better than chance on this task. In a more common mass judgment, Runeson and Frykholm (1981; 1983) found that observers were highly accurate at estimating the absolute weight of objects that they saw being lifted by another person, both under full illumination and with only patch lights visible on the actor’s joints. Bingham (1987) has investigated the biomechanical basis for kinematic information used in such judgments of lifted weight.

Similar results have been obtained for the perception of other environmental properties. Infants and adults have been shown to distinguish rigid and plastic objects based on their patterns of rigid motion or deformation (von Fieandt and Gibson 1959; Gibson et al 1978; 1979; Todd 1982). Pittenger (1985) found ordinarily correct
judgments of the length of a pendulum when only the oscillation of the top 8 cm of its arm was visible, although absolute judgments underestimated true length. When presented with completely visible anomalous pendula whose swing frequencies were inappropriate for their lengths, observers were quite accurate at rating them as “too fast” or “too slow” (Pittenger 1986). Observers can even make reliable judgments of the animacy and intentions of moving objects on the basis of their spatiotemporal patterns of motion (Bassili 1976; Heider and Simmel 1944; Stewart 1984). In short, numerous physical and other environmental properties can be perceived with reasonable accuracy if observers have access to kinematic information that adequately specifies them, even though cognitive concepts of physical principles may be erroneous. We will return to this contrast below.

In the experiments reported here we develop the line of research on kinematic information for dynamic properties established by Runeson (1977a, 1983) and Todd and Warren (1982), examining the perception of elasticity in bouncing events. The term ‘elasticity’ refers to how readily an object returns to its initial shape after deformation, and is formalized by the coefficient of restitution, \( e \), which varies between 0 and 1. Elasticity is a characteristic of a two-body system; in the case of a bouncing object, one body is an essentially stationary ground surface that can be regarded as constant in a given situation, such as a gym floor. The vertical motion of the bouncing object is then determined by its initial height of release, gravitational acceleration, and the coefficient \( e \): a system with \( e = 0 \) would have no rebound, whereas one with \( e = 1 \) would continue bouncing in perpetual motion. Several different aspects of the bouncing pattern uniquely specify elasticity independent of initial height, assuming constant gravitational acceleration (see experiment 2).

Bouncing objects are common in the human environment and perceiving their elasticities can be useful for controlling behavior. For example, a recent rule change in intercollegiate women’s basketball in the United States of America mandated a switch to a smaller and more elastic ball, so that players had to perceive and adapt to the new elasticity in order to control dribbling (repeatedly bouncing the ball on the floor) and bounce passing. Slight variations between balls also require rapid adjustments during practice drills in which different balls are used in quick succession.

In experiment 1 we determined whether untrained observers could perceive the elasticity of a bouncing ball on the basis of visual and auditory information in order to control a bounce pass. We also examined several hypotheses about which parameters of the throwing action are regulated by perceptual information. In experiments 2 and 3 we used computer-generated displays to test the kinematic variables that observers use in making visual judgments of bounciness. Finally, in experiment 4 we determined whether observers use the same amodal information in the visual and auditory modalities.

2 Experiment 1: control of the bounce pass
The first experiment was designed to determine whether information about elasticity could be detected and used for the successful control of action. In order to minimize cognitive contributions, we made direct measures of motor performance rather than using verbal judgments or ratings. The task was to bounce a ball off the floor to a constant target height after exposure to various sources of information about the elasticity of the system.

We used four information preview conditions:

(1) in the auditory condition participants heard the ball bounce several times before they bounced it to the target height;
(2) in the auditory–visual (AV) condition they both saw and heard the ball bounce;
(3) in the self-bounce condition they actively dribbled the ball themselves; and
(4) in the no-preview condition there was no prior exposure to the ball.
Some haptic information about the compliance of the ball was available in all conditions when the subject handled the ball, and the no-preview condition served as a control for information obtained by touch. If auditory and/or visual information can be used more effectively than haptic information, then the accuracy of the bounce pass should be greater in the first two conditions than in the no-preview control. The self-bounce condition allowed us to compare perception of a distant object with active exploration of the object’s behavior, during which the consequences of applying a known force to the ball could be determined.

A secondary aim of experiment 1 was to determine which parameters of the action of throwing are regulated by AV information about elasticity. Warren (to be published) has suggested that adaptive action is achieved by allowing visual information to modulate the free parameters of an otherwise self-organized action system that has adopted a task-specific mode of organization for an action such as throwing. Warren et al (1986) proposed such a model for the visual control of step length in human running, whereby the vertical impulse applied by the runner during the stance phase is directly regulated by optical time-to-contact information about upcoming clear patches of ground. In the present case, certain parameters of the throw may be modulated by perceptual information about the elasticity of the system, in order to achieve the same final height near the target line.

A simple model of the bounce pass, derived from the equations of motion (see Appendix 1), is represented by

$$h_f = \frac{2(hr + \frac{I^2}{2})}{2gm^2}$$

where the final peak height of the ball $h_f$ is a function of the system’s elasticity $e$, the height of the ball when it is released from the thrower’s hands $h_r$, the impulse $I$ applied during the throw, gravitational acceleration $g$, and the mass $m$ of the ball. This immediately leads to several hypotheses about how the actor could regulate the throw to adjust for changes in elasticity, assuming $m$, $g$, and $h_f$ to be constant.

(i) **Release-height hypothesis.** To compensate for a decrease in elasticity, the thrower could increase the height from which the ball is released. From equation (1), this hypothesis predicts a high correlation between $h_r$ and $1/e^2$. For the range of elasticities in this experiment ($e = 0.63$ to 0.85), varying release height alone would require a range of adjustment of 2.0 m, which is highly unlikely.

(ii) **Impulse hypothesis.** Alternatively (or in addition), the thrower could increase the impulse applied to the ball during the throw—that is, throw it ‘harder’. This hypothesis predicts a high correlation between $I^2$ and $1/e^2$. If this is indeed the case, changes in impulse may be related to changes in other parameters. Because impulse, due to both active muscle contributions and the passive effect of gravity, is equal to the change in momentum of the ball from the peak of the throw (where $v = 0$) to the moment of release (where $v = v_r$), then

$$I = m(v_r - 0) = \frac{2md}{t}$$

where $v_r$ is the release velocity, $d$ is the distance through which the ball is moved during the throw, and $t$ is the duration of the throw. This suggests two subsidiary hypotheses.

(iii) **Throw-time hypothesis.** From equation (2), an increase in impulse could be associated with a decrease in the duration $t$ of the throw, which predicts a high correlation between $I$ and $1/t$. Varying throw time alone would require a range of adjustment of about 0.078 s under our experimental conditions, which is quite reasonable.
(iv) *Throw-distance hypothesis.* Alternatively (or in addition), an increase in impulse could be associated with an increase in the distance \( d \) from the peak height of the throwing motion to the height of release, which predicts a high correlation between \( I \) and \( d \). Varying throw distance alone would require a range of adjustment of about 0.23 m under our conditions, which is also reasonable.

In sum, our aims in the first experiment were to see whether actors can appropriately control the bounce pass on the basis of perceptual information about elasticity, and to determine what parameters of the throw are regulated by AV information.

### 2.1 Method

#### 2.1.1 Subjects.
Twelve undergraduates, seven male and five female, volunteered to participate in the experiment. None of them had taken a college-level physics course, and none were intramural or varsity athletes.

#### 2.1.2 Equipment.
Five rubber balls, each 21 cm in diameter, were used in all conditions. Elasticities were set to approximately \( e = 0.64, 0.70, 0.76, 0.82, \) and 0.88 by filling the balls with foam rubber, cloth, or Styrofoam chips, and by adjusting air pressure before each test session. The mean elasticities determined empirically from the videotapes were actually \( e = 0.63, 0.66, 0.74, 0.80, \) and 0.85, and these values were used in later analysis. This manipulation resulted in slight differences in compliance, such that the two most elastic balls were perceptibly harder to the touch than the other three. In all other respects the balls were identical, including their weight (0.37 kg), size, color, and other markings.

The experiment was performed in a gymnasium with a wooden floor and cinder block walls. The walls were painted grey below a height of 179 cm and white above it; this line served as the target height for the bouncing task. Two vertical scales, each 30 cm wide and marked at 10 cm intervals, were mounted on one wall, 50 cm apart. The participant stood between the two scales and was videotaped with an RCA camera placed at the height of the target line 4.6 m from the wall. Trials were recorded on an RCA video cassette recorder at a sampling rate of 30 Hz, with an on-screen clock calibrated in units of 0.01 s.

#### 2.1.3 Procedure.
Subjects were tested individually and each received all four preview conditions. They were told that the five balls varied only in their ‘bounciness’, were instructed to bounce them vertically so that the bottom of the ball just reached the target line, and were explicitly told not to squeeze a ball before bouncing it. The experimenter demonstrated the task, and the subject then practiced bouncing the least elastic ball and the most elastic ball once to the target line. Each preview condition consisted of brief instructions followed by a block of twenty-five trials, five with each ball, for a total of one hundred trials. The balls were presented in a random order and the order of conditions was counterbalanced across subjects to control for practice effects. An experimental session lasted ~30 min.

In the *auditory condition*, before each trial the experimenter dropped the ball behind the subject from a randomly varied height of 1 to 2 m and allowed it to bounce four to six times, so that only its bouncing pattern could be heard. The ball was then handed to the subject, who attempted to bounce it to the target line. Thus, auditory and haptic information about the ball was available in this condition. In the *auditory-visual (AV) condition*, the experimenter dropped the ball in the subject’s field of view before each trial, again from a randomly varied height, and allowed it to bounce four to six times. In this case, visual, auditory, and haptic information was available. In the *self-bounce condition*, the subject dribbled the ball twice before attempting to bounce it to the target line. In this case, the consequences of applying a known force to the ball could be detected visually or haptically, although the types of visual and auditory information
available in the first two conditions were not available here (see experiment 2). Finally, in the no-preview condition, subjects were given as little information as possible about the ball. A ball was simply handed to the subject on each trial, and thus only haptic information was available.

The videotapes were scored by hand, using single-frame analysis. Bounce error—the distance between the target line and the bottom of the ball at the highest point in its trajectory—was measured on each trial to the nearest 2 cm. Additional measurements of the throw were made on trials from the AV condition only, and included the actual elasticity $e$, the height $h_p$ and time $t_p$ at the peak of the throwing motion, and the height $h_r$ and time $t_r$ at the ball's release. From these data the distance $d$, time $t$, mean force $F$, and impulse $I$ of the throw were calculated. The precision of these data is limited by the videotape's temporal resolution of 30 Hz, which resulted in maximum errors of $\pm 0.016$ s in measurements of $t$ and $\pm 0.15$ m in measurements of $h_r$ (assuming the maximum mean release velocity of $v_r = 9.51$ m s$^{-1}$ for the least elastic ball). On the other hand, measurements of $h_p$ and $h_r$ were accurate to $\pm 0.02$ m because the ball slowed to a stop at the peak of its motion. Since measurement error is random, averaging over measurements reduces its effect and increases the effective resolution. Impulse was computed in two ways, one based on position measurements (see Appendix 1) and relatively immune to moderate error in $h_r$,

$$I = \frac{m}{2g} \left[ \frac{h_r}{e^2} - h_r \right]^{1/2},$$

and the other based on time and position measurements and more sensitive to error,

$$I' = \frac{2md}{t}.$$

The mean of normalized individual correlations between $I$ and $I'$, $r_m$, was 0.73, indicating the empirical effect of measurement errors. Consequently, certain conclusions about these action parameters should be regarded as preliminary.

2.2 Results and discussion

2.2.1 Accuracy. A measure of overall accuracy in each condition is provided by the mean absolute error, which was 16.9 cm in the self-bounce condition, 20.5 cm in the AV condition, 22.9 cm in the auditory condition, and 28.2 cm in the no-preview condition. An analysis of variance (condition x elasticity) yielded a main effect of preview condition ($F_{3,33} = 30.86, p < 0.001$), and a main effect of elasticity ($F_{4,44} = 4.17, p < 0.01$), but no interaction. A posteriori Tukey tests revealed significant differences between all conditions at the $p < 0.01$ level, with the exception of the difference between AV and self-bounce at the $p < 0.05$ level, and that between auditory and AV, which was not significant. These results indicate that subjects used both auditory and AV information about elasticity to control the bounce pass with reasonable accuracy. Although the addition of visual information improved performance slightly over auditory information alone, the improvement was not statistically significant. The self-bounce condition, in which subjects could see and feel the effects of applying a known force to the ball, yielded the most accurate performance.

Another way of looking at the data is presented in figure 1, in which mean error (incorporating negative values for undershooting the target) is plotted for each ball in each condition. An analysis of variance (condition x elasticity) on mean error revealed no condition effect ($F_{3,33} = 0.85$), an elasticity effect ($F_{4,44} = 33.75, p < 0.001$), and an interaction ($F_{12,33} = 12.26, p < 0.001$), reinforcing the differences between types of information. First, it is apparent that the greatest accuracy in each condition was achieved with a ball near the middle of the elasticity range. All the curves cross zero
error at approximately the same point, indicating that the impulse applied during the throw was generally biased toward that appropriate for a ball of $e = -0.73$; more elastic balls generally overshot the target and less elastic ones undershot it. This value is almost precisely the midpoint of the range of elasticity tested ($e = 0.74$), which corresponds to the midpoint of the range of required throwing impulse tested ($I = 2.716$ N s at the mean release height of 65 cm); the relation between elasticity and the impulse required to reach the target is approximately linear over this range. In addition, it may also be close to the middle of the normal range of impulse for all throws of this type, for subjectively the least elastic ball required an extremely hard throw ($I = 3.218$ N s) and the most elastic ball required a very light throw ($I = 2.214$ N s).

Second, the slopes of the curves in figure 1 indicate the accuracy of performance in each condition. A horizontal line at zero error would indicate perfect adjustment for changes in elasticity, and the thin line in figure 1 indicates the error that would occur if no adjustment were made, that is, if a constant impulse appropriate for a ball of $e = 0.73$ were applied on each throw ($I = 2.696$ N s). The curve closest to the horizontal represents the self-bounce condition, although even here participants did not fully adjust for elasticity. This failure to increase the impulse of the throw sufficiently at low elasticities and to reduce it sufficiently at high elasticities could be due to 'under-perceiving' the extreme values of elasticity, or to a lability in the action system that biases the throw toward the middle of the impulse range. To provide a sense of scale, however, a failure to adjust for a change in elasticity of 0.1 would yield errors of ~50 cm under our conditions, and thus the observed errors of 10–20 cm in the self-bounce and AV conditions indicate a substantially greater sensitivity. We will return to this question in experiment 4. At the other extreme, the curve closest to the no-adjustment line represents the no-preview condition, but the difference between them indicate that some adjustments were made even in this condition on the basis of haptic information alone.

![Figure 1](image-url)
2.2.2 Action parameters. Given that subjects can use visual and auditory information about elasticity, what parameters of the throw are regulated by such information? We examined the four hypotheses by calculating correlations between the relevant action variables for each subject (twenty-five data points in each correlation), normalizing them by converting to $z_r$, computing means across the twelve subjects, and converting them back into mean correlation coefficients $r_m$. These values appear in table 1.

Table 1. Mean correlations $r_m$ for action parameters in experiment 1.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>$r_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release height ($1/e^2$ with $h_r$)</td>
<td>-0.11</td>
</tr>
<tr>
<td>Impulse ($1/e^2$ with $I^2$)</td>
<td>0.83***</td>
</tr>
<tr>
<td>Throw time ($I$ with $1/t$)</td>
<td>-0.29</td>
</tr>
<tr>
<td>Throw distance ($I$ with $d$)</td>
<td>0.52**</td>
</tr>
<tr>
<td>Throw peak ($I$ with $h_p$)</td>
<td>0.58**</td>
</tr>
<tr>
<td>Mean force ($I$ with $F$)</td>
<td>0.59**</td>
</tr>
</tbody>
</table>

** $p < 0.01$; *** $p < 0.001$.

(i) Release-height hypothesis. The mean correlation between $h_r$ and $1/e^2$ [$r_m(23) = -0.11$] was not significant, indicating that release height did not covary with elasticity. In fact, the mean release height varied very little within each subject's performance (mean = 0.65 m, mean subject SD = 0.087 m), and we will regard it as approximately constant.

(ii) Impulse hypothesis. However, the mean correlation between $I^2$ and $1/e^2$ [$r_m(23) = 0.83$, $p < 0.001$], was strong, indicating that impulse was varied to adjust for changes in elasticity. This is similar to the finding that impulse is the regulated parameter in the control of step length during running (Warren et al 1986). What related variables are affected?

(iii) Throw-time hypothesis. The mean correlation between $1/t$ and $I$ [$r_m(23) = -0.29$], was not statistically different from zero. This indicates that throw time did not vary reliably as the inverse of impulse, and the trend was actually in the opposite direction.

(iv) Throw-distance hypothesis. The correlation between $d$ and $I$ was higher [$r_m(23) = 0.52$, $p < 0.01$]. Thus, an increase in impulse was accompanied by an increase in the distance of the throw but its duration was held roughly constant. This implies two things: (a) Since release height was also roughly constant, subjects must have increased the peak height of the throw. This is confirmed by the mean correlation [$r_m(23) = 0.58$, $p < 0.01$] between $I$ and $h_p$. (b) Since $I = Ft$ and $t$ was constant, subjects must have increased the mean force applied during the throw. This is confirmed by the mean correlation [$r_m(23) = 0.59$, $p < 0.01$] between $I$ and $F$. Thus, subjects regulated the throw by increasing its peak height and mean force, resulting in an approximately constant duration. This behavior is qualitatively similar to that of a mass-spring that is stretched to a greater initial position, which yields a higher acceleration but maintains a constant period.

These conclusions about throw time and throw distance should be regarded as preliminary, given possible measurement error in $t$ and $d$. The relatively high correlation for the throw-distance hypothesis indicates that measurement error for $d$ did not swamp its relationship with $I$, but the low correlation for the throw-time hypothesis might be attributed to error. However, whereas the expected range of adjustment in $d$ was only 0.7 of its range of error, the expected range of adjustment in $t$ was fully
2.4 times its range of error, indicating that a correlation over this range should have been detectable if it existed. Nevertheless, this does not rule out the possibility that \( t \) varies systematically in combination with \( d \) over a much narrower range that is below our scale of resolution. It is safe to conclude that subjects adjusted the bounce pass for changes in perceived elasticity by modulating the impulse applied during the throw, perhaps by varying the mean force and peak height of the throw while holding throw duration roughly constant.

Thus we have shown in experiment 1 that numerous sources of information about elasticity are available to an active observer via the visual, auditory, and haptic modalities and can be detected with varying degrees of success. The results demonstrate that subjects can perceive elasticity and appropriately regulate the impulse applied to the ball during a bounce pass, albeit with some systematic undershooting and overshooting. In experiments 2 and 3 we tested specific hypotheses about the effective visual information for elasticity.

3 Experiment 2: visual information for elasticity

The results of the first experiment show that subjects can appropriately adjust their actions on the basis of visual and auditory information about elasticity. However, the question as to which kinematic variables they detect remains. In experiment 2 we examined visual information for elasticity under more controlled conditions by manipulating computer-generated displays of a bouncing ball and obtaining ratings of perceived bounciness.

The kinematics of a bouncing pattern contain at least three sources of optical information specific to elasticity, which can be derived from the equations of motion for collisions (see figure 2 and Appendix 2). All three types of information must be detected over time, hence none are available in a static image of a bouncing object.

![Figure 2. Sources of visual information for elasticity](image)

(i) Relative height hypothesis. The elasticity of a ball/floor system is specified by the change in the peak height of the trajectory of the ball on any one bounce, specifically, the square root of the ratio of final height \( h_2 \) to initial height \( h_1 \):

\[
e = \left( \frac{h_2}{h_1} \right)^{1/2}
\]

This information is available to a viewer over one complete cycle of bouncing, between any two successive peak heights.
Relative period hypothesis. Elasticity is also specified by the change in cycle duration or period on successive bounces, specifically by the ratio of one period \( \tau_2 \) to the previous period \( \tau_1 \):

\[
e = \frac{\tau_2}{\tau_1}.
\]

This is available over any two successive cycles of bouncing, defined by three consecutive collisions (or three consecutive peaks). It is interesting to note that relative period information is the only source available both visually and auditorily, when defined over three visible or audible collisions. Because the information receives the same abstract description in both the optical and acoustical domains, it is an example of amodal information. If humans can use amodal period information, performance should be equivalent in the two modalities; this hypothesis is tested in experiment 4.

Relative velocity hypothesis. Finally, elasticity is also specified by the instantaneous change in velocity on any one bounce, specifically the ratio of rebound velocity \( v_2 \) to incident velocity \( v_1 \):

\[
e = \frac{v_2}{v_1}.
\]

This information is available in a single collision.

In this experiment we attempted to isolate each source of visual information to test its sufficiency for the perception of bounciness. First, in the full information condition, three to five completely visible bounces were displayed to provide a standard of maximal performance. Second, relative height information was isolated by masking the collisions of the ball with the ground, but leaving its initial and final heights visible. Third, relative period information was isolated by masking all of the trajectory except the point at which the ball was in contact with the ground. Fourth, relative velocity information was isolated by masking the upper portion of the trajectory of the ball, but leaving its incident and rebound velocities visible. Finally, a slow velocity condition was included to determine whether performance with velocity information could be improved by simulating a ball dropped from a greater height. In sum, in experiment 2 we sought to determine which of the three available sources of visual information observers can use to perceive elasticity.

3.1 Method

3.1.1 Subjects. Three groups of subjects participated in the experiment. Group A consisted of twenty-four undergraduates, twelve male and twelve female, who received the original four conditions in a within-subject design. However, we subsequently discovered that there was an error in the program that generated the relative velocity displays, invalidating the data from that condition and leading us to run two follow-up conditions. Group B contained ten additional subjects, five male and five female, who received a corrected replication of the relative velocity condition, and it is these data that were analyzed. Group C contained ten other subjects, five male and five female, who received the slow velocity condition in an effort to examine velocity information further. None of the subjects had taken a college-level physics course, and none had participated in experiment 1.

3.1.2 Displays. Animated displays of a white circle moving vertically on a black background were generated on a Terak 8510/a microcomputer, updated at a rate of 12 frames s\(^{-1}\). The displays simulated a ball, 31 cm in diameter, bouncing at a distance of 22.2 m from the subject in a gravitational field of \( g = 9.8 \) m s\(^{-2}\). The ground was represented by a horizontal white line at the bottom of the screen. Subjects viewed the
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screen from a distance of ~50 cm and the ball subtended a visual angle of ~0.8 deg. The ball appeared on screen at a randomly selected starting height above the ground and its bouncing pattern was determined by the equations of motion for a falling body. Each collision always included one frame in which the ball was in contact with the ground, but no compression of the ball was depicted, since it is typically not visible in real collisions.

Elasticity was selected randomly on each trial from nine possible values (0.50, 0.55, 0.60, ..., 0.90), and the simulated starting height was selected randomly from five possible values (4.0, 4.5, 5.0, 5.5, 6.0 cm above the ground, 10.3 to 15.4 deg of visual angle). The same values were used in all conditions and were selected to insure that the ball bounced high enough with respect to the various masks. The randomization was constrained to yield one trial for each combination of starting height and elasticity, for a total of forty-five trials in each condition.

In the original experimental design, all twenty-four subjects participated in four experimental conditions. In the full information condition, a fully visible bouncing ball was displayed. The number of collisions on each trial varied randomly between three, four, or five, yielding displays that ranged in duration from 2.36 to 8.27 s. Varying starting height and the number of collisions insured that extraneous display variables did not uniquely covary with elasticity, such that the correlation \( r \) between elasticity and display duration was 0.81, and that between elasticity and the number of bounces was 0. Thus, we could evaluate the effects of these variables on elasticity ratings in this condition, but we could not do so in other conditions because only three bounces were possible for the masks to be effective.

In the relative height condition, a white mask appeared on the bottom portion of the screen, occluding the last 1.0 m (2.6 deg) of the ball's simulated trajectory above the ground, and thus its change in velocity upon contact with the ground. The ball appeared at the starting height and bounced on the ground twice, the display ending upon the second collision. The height of the mask was chosen so that the initial and final height of one complete bouncing cycle were visible above it on all trials, isolating relative height information. The mask was displayed continuously for all forty-five trials and the displays varied in duration from 1.86 to 3.21 s. Loosely speaking, a type of relative velocity information was also available in this condition: the ratio between the velocity of the ball at its point of disappearance behind the mask to that at its reemergence, although this ratio does not uniquely covary with elasticity. However, an improvement in this condition over the relative velocity condition would provide evidence for the use of relative height information.

In the relative period condition, a large white mask filled the upper portion of the screen so that only 0.35 m (0.9 deg) of the simulated trajectory was visible above the ground, just slightly more than the ball itself (0.31 m, 0.8 deg). Three successive collisions between the ball and the ground were displayed on each trial, and the ball was only visible for one to four frames (0.084 to 0.337 s) below the mask, depending on starting height and elasticity. Relative velocity information was also available from those collisions in which three or four frames were visible, but again an improvement in this condition over the relative velocity condition would provide evidence for the use of period information.

In the relative velocity condition, a large white mask filled the upper portion of the screen so that the ball was visible for a simulated 0.98 m (2.3 deg) between the bottom of the mask and the ground. The ball only bounced once on a given trial and was visible below the mask for three to five frames (0.252 to 0.420 s) depending on starting height and elasticity. The height of the mask was chosen so that the initial and final heights of the trajectory of the ball were occluded on all trials, thus isolating relative velocity information. This condition was presented to the ten subjects in group B.
Finally, the brief exposures of 252 to 420 ms in the relative velocity condition raised the possibility that subjects might be at a disadvantage in detecting relative velocity information compared to the other conditions. Although these temporal constraints are comparable to many studies of apparent motion and subjects were under equally severe constraints in the relative period condition, we wanted to make sure that they had sufficient time to detect relative velocity and so ran a fifth condition with ten subjects in group C. In this slow velocity condition we changed the display parameters so as to preserve all of the visual angles in the display but slow down the ball. We simulated a large ball, 1.24 m in diameter, bouncing at a distance of 88.8 m, with starting height selected randomly from five larger values (16, 18, 20, 22, 24 m) and elasticity values remaining the same as in previous conditions. The ball was visible below the mask for five to twelve frames (0.420 to 1.008 s). If subjects are capable of using relative velocity information, these rather extreme conditions would provide an optimal opportunity to do so.

3.1.3 Procedure. The four original conditions were presented to group A in a within-subject design, counterbalanced for order. Subjects were tested individually while seated in front of the display screen in a dimly lit room. They were instructed to "judge how bouncy the ball looks on a scale of 1 to 9, where 1 is least bouncy and 9 is most bouncy", typing their ratings on the computer keyboard. The rating scale appeared on a card below the screen. The endpoints of the scale were demonstrated in four sample trials, displaying the least and most bouncy balls dropped from the lowest and highest heights, with the experimenter indicating the correct response. Ten full information practice trials were then presented without feedback, followed by forty-five test trials in each of the four conditions, for a total of one hundred and eighty test trials. The observer's response initiated the next trial, and no feedback was provided. Brief instructions were given before each condition, with the experimenter describing the display and repeating the rating instructions, but no further practice trials were presented. Data on elasticity, starting height, number of bounces, display duration, and the observer's rating for each trial were recorded by the computer. During debriefing, the subject was asked to rank order the conditions for difficulty. An experimental session lasted ~40 min.

The two follow-up conditions were presented to group B and to group C in a between-subject design. In these conditions, the four sample trials and ten practice trials were identical to the subsequent test trials. Each group received forty-five test trials, and a session lasted ~15 min. Otherwise, the procedure was identical to that in the original conditions.

3.2 Results and discussion

Mean bounciness ratings for the full information, relative height, relative period, and relative velocity conditions are plotted in figure 3. The curve for the full information condition follows closely along the diagonal, and those for the other conditions are increasingly flatter, primarily because of the higher ratings at low elasticities. An analysis of variance (condition × elasticity) on the data from group A in the first three conditions revealed a main effect of elasticity ($F_{8,184} = 581.39, p < 0.01$), a main effect of condition ($F_{2,46} = 3.26, p < 0.05$), and a significant interaction ($F_{16,368} = 6.58, p < 0.001$).

To analyze the accuracy of the ratings in more detail, we calculated the correlation between bounciness rating and elasticity for each subject, and mean correlations $r_m$ for each condition were computed using normalized $z_r$. These values appear in figure 4. A linear regression of rating on elasticity was also computed for each subject, and mean regression slopes $b_m$ were determined for each condition.
Perception of elasticity

We then performed two analyses of these data: a within-subject analysis of variance on the data from group A, and a separate between-subject analysis of variance on the relative period, relative velocity, and slow velocity conditions from groups A, B, and C. The main methodological problem with the latter analysis is a possible practice effect for group A in the relative period condition, owing to the fact that this group also received the two other original conditions. This could yield artificially high performance with relative period. However, a t-test for an order effect comparing the normalized correlations of the six subjects who received the relative period condition first with those of the six who received it last showed no effect of practice ($t_{10} = 0.26$). Hence, we believe that we can legitimately compare the period condition with the two follow-up conditions, thereby tying these two sets of results together.

![Figure 3](image3.png)

**Figure 3.** Mean bounciness rating (1 = least bouncy, 9 = most bouncy) as a function of elasticity $e$ for the full information, relative height, relative period, and relative velocity conditions in experiment 2. Thin line indicates perfect performance.

![Figure 4](image4.png)

**Figure 4.** Mean correlations between bounciness rating and elasticity for each information condition in experiment 2. Asterisks indicate statistically significant differences by grouping conditions for which no differences were found.

3.2.1 *Original conditions (group A).* An analysis of variance was performed on the normalized correlations ($z_i$) for the full information, relative height, and relative period conditions. A similar analysis was performed on regression slopes. Both analyses yielded a significant effect of condition: $F_{2,46} = 58.28$, $p < 0.001$ for the correlations, and $F_{2,46} = 13.98$, $p < 0.001$ for the slopes. To examine the relationships among particular conditions, we performed a posteriori Tukey tests; the results are indicated by asterisks in figure 4 and we will discuss them in detail here.
In the full information condition, the mean correlation was very high ($r_m = 0.91$), with little variation across the twenty-four subjects (range = 0.82 to 0.94). In addition, the mean slope ($b_m = 16.91$) was close to a 'perfect' slope of 20. These results indicate that all subjects were highly accurate in perceiving elasticity when full visual information was available.

The results were similar in the relative height condition for the mean correlation ($r_m = 0.88$, range = 0.78 to 0.94), with a slightly depressed mean slope ($b_m = 14.47$). Although the differences between these first two conditions are statistically significant at the $p < 0.05$ level for the correlations and the $p < 0.01$ level for the slopes, in absolute terms the correlation is nearly as strong with relative height information alone as with full information. Possible reasons for the statistical difference are discussed below.

The correlation dropped substantially in the relative period condition ($r_m = 0.79$, range = 0.59 to 0.87), although the mean slope ($b_m = 14.52$) was statistically indistinguishable from the relative height condition. The decrement in the correlation was significant at the $p < 0.001$ level when compared with both the relative height and the full information conditions. This indicates that subjects were not as sensitive to period information as they were to height information, but, as in experiment 1, were able to make some use of it.

3.2.2 Follow-up conditions (groups A, B, C). Analyses of variance for unequal $N$ were performed on the normalized correlations and on the regression slopes to compare the relative velocity, slow velocity, and relative period conditions. The analysis of correlations produced a significant effect of condition ($F_{2,41} = 8.56$, $p < 0.001$), and that for slopes was marginally significant ($F_{2,41} = 3.01$, $p < 0.06$). A posteriori Tukey tests were performed on the correlations to compare individual conditions and are reported here and indicated in figure 4.

Performance in the relative velocity condition dropped still further with respect to the relative period condition ($r_m = 0.63$, range = 0.49 to 0.74; $b_m = 11.73$). The difference between the correlations in these two conditions was significant at the $p < 0.01$ level. Thus, subjects did not appear to make effective use of relative velocity information in perceiving elasticity, at least within the temporal constraints of these displays.

The slow velocity condition relaxed these constraints somewhat, giving subjects more than twice as long to pick up relative velocity information. Accuracy improved somewhat ($r_m = 0.73$, range = 0.36 to 0.85; $b_m = 13.71$), but owing to the high variability these improvements were not statistically significant. Thus, even under favorable conditions, most subjects did not appear to make effective use of relative velocity information. This result supports the claim that the high level of accuracy in the relative height condition cannot be explained by the availability of weak relative velocity information in that condition, but must be attributed to relative height information per se.

This general pattern of results is corroborated by the rank orderings of condition difficulty made by the subjects themselves. Twenty out of the original twenty-four subjects ranked the conditions in the order indicated by the correlations, from easiest to hardest: full, relative height, relative period, relative velocity. The possibility that subjects based their ratings on extraneous display variables was tested using data from the full information condition. The mean correlation between subject rating and number of bounces was negligible ($r_m = 0.03$). The mean correlation between rating and display duration was significantly lower ($r_m = 0.78$) than the mean correlation between rating and elasticity based on tests for the difference between two related values of $r$ on each subject's data ($z_m = 2.33$, $p < 0.05$). Thus, subjects did not rely on the extraneous variables of number of bounces or display duration in the full information condition, or, presumably, in the other conditions.
In sum, in experiment 2 we have demonstrated that observers can perceive elasticity quite accurately when full information is available. The pattern of results indicates that they do this primarily by using relative height information. Performance declines when only relative period information is available, and little use is made of relative velocity information. The comparable accuracy in the relative height and full information conditions suggests that observers rely solely on relative height when all sources of information are concurrently available. It seems likely that the small but statistically significant difference between these two conditions is due to the repetition of relative height information two to four times in each display in the full information condition, whereas it occurred only once in the relative height condition. Thus, an inattentive observer who missed relative height on the first bounce could detect it on the second, third, or fourth bounce. We doubt that the difference is due to a redundancy gain from concurrently available relative period or velocity information, because the ability to detect them is markedly poorer.

However, it is premature to conclude that observers are detecting relative information in these conditions, for several competing hypotheses of simpler variables remain to be tested.

4 Experiment 3: higher-order ratios or simple variables?
Although relative height, relative period, and relative velocity information were isolated from each other in experiment 2, several competing hypotheses remain. Rather than use such higher-order ratios to perceive bounciness, subjects could be relying on simpler aspects of the bouncing pattern, specifically a single peak height, a single period duration, or a single rebound velocity. These simple variables do not covary uniquely with elasticity, but vary as a function of both elasticity and starting height. However, under the conditions of experiment 2, there were high correlations (all $r > 0.92$) between the simple variables and elasticity. Thus, subjects could have achieved the observed levels of performance by relying on them rather than on the higher-order ratios.

In this experiment we used different ranges of starting height in order to decorrelate simple variables from their higher-order ratios and thus test these three competing hypotheses: (i) the **height condition** tested the single peak height hypothesis by decorrelating final peak height $h_z$ from relative height; (ii) the **period condition** tested the single period hypothesis by decorrelating the first ($\tau_1$) and second ($\tau_2$) period durations from relative period; and (iii) the **velocity condition** tested the single velocity hypothesis, by decorrelating the rebound velocity $v_z$ and relative velocity on one bounce. If observers use higher-order relative information their ratings should correlate more strongly with true elasticity $e$ than with the simple variables.

4.1 Method
4.1.1 Subjects. Twelve undergraduates, six male and six female, were paid to participate in the experiment. None of them had taken a college-level physics course, and none had participated in the previous experiments.
4.1.2 Displays. Animated displays of a bouncing ball were similar to those in experiment 2, with the following changes. In all three conditions elasticity was selected randomly from a slightly narrower range of seven values (0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90), to ensure that the ball would bounce high enough with respect to the various masks. In the height condition the simulated starting height was selected randomly from a wider range of four values (3, 4, 5, 6 m above the ground, 7.7 to 15.4 deg). To ensure that the peak heights remained visible, the mask that filled the bottom portion of the screen was somewhat lower, occluding the last 0.7 m (1.8 deg) of the simulated trajectory of the ball. The net result was to create a wider range of final peak heights, such that the correlation $r$ between $e$ and $h_z$ was lowered from 0.92 to
0.71; that between $e$ and $h_1$ remained at 0. There were fifty-six test trials in this condition. In the period condition, starting height was varied between a much wider range of five values (2, 4, 6, 8, 10 m), which reduced the correlation $r$ between $e$ and $\tau_1$ from 0.93 to 0.45, and that between $e$ and $\tau_2$ from 0.97 to 0.70 ($\tau_1$ and $\tau_2$ retained a high correlation of $r = 0.95$). There were seventy test trials in this condition. Finally, in the velocity condition, starting height was varied between four values (3, 4, 5, 6 m), reducing the correlation $r$ between $e$ and $v_1$ from 0.93 to 0.72; that between $e$ and $v_2$ remained at 0. There were fifty-six test trials in this condition.

4.1.3 Procedure. The three conditions were presented to all subjects in a within-subject design, counterbalanced for order. Subjects received four sample trials that demonstrated the endpoints of a 1 to 7 rating scale, and then received ten practice displays, both using displays from the first condition they were to receive. Subsequent conditions were preceded by brief instructions, but no further practice. During debriefing, subjects were asked what aspects of the display they thought they were "paying attention to". An experimental session lasted ~45 min. Otherwise, the procedure was the same as in experiment 2.

4.2 Results and discussion

Correlations were performed between observer ratings of bounciness and the three display variables for each subject in each condition. For example, in the height condition, correlations were computed between ratings and each of the variables $h_1$, $h_2$, and $e$ (which corresponds to relative height). Mean correlations for each condition were calculated using normalized values of $z_r$ and are given in figure 5. To compare these correlations, two-tailed tests for a difference between two related values of $r$ were performed for each observer. The resulting $z$ scores for the difference were then averaged to obtain a group mean $z_m$ score, which was evaluated for its significance level. The results of these tests within each condition are indicated with asterisks in figure 5. Finally, $t$-tests on the normalized $Z_r$ in each condition revealed no gender differences in the correlations between ratings and elasticity.

Height. The strongest correlation in the height condition was between subject rating and elasticity ($r_m = 0.87$), and was nearly identical to the results of experiment 2. This correlation was significantly greater than that between rating and $h_2$ ($r_m = 0.71$; $z_m = 2.45$, $p < 0.05$), and that between rating and $h_1$ ($r_m = 0.13$; $z_m = 5.36$, $p < 0.001$). This pattern of results indicates that subjects were basing their perceptual judgments on relative height information, which uniquely specifies elasticity, rather than on the simple variables of final or initial peak height. This corresponds with the results of the debriefing, in which 100% of the subjects reported that they were attending to relative height.

![Figure 5. Mean correlations between bounciness rating and display variables for each information condition in experiment 3. Asterisks indicate statistically significant differences. $h_1$, starting height; $h_2$, rebound height; $\tau_1$, first period; $\tau_2$, second period; $v_1$, incident velocity; $v_2$, rebound velocity; $e$, elasticity.](image-url)
Period. In contrast, in the period condition the mean correlation between rating and elasticity \((r_m = 0.76; z_m = 2.23, p < 0.05)\) was significantly lower than that between rating and \(\tau_1\) \((r_m = 0.55; z_m = 3.08, p < 0.01)\). The latter two correlations were not statistically different \((z_m = 1.10)\). Only one subject showed the reverse result, having a correlation with \(e\) that was significantly greater than those with the single periods. Thus, subjects did not seem to use relative period information, but based their ratings of bounciness on the duration of a single period; the nonsignificant trend suggests that subjects relied on final period. These findings are at odds with what subjects said they were doing, for 100% of them reported that they were attending to the change in period over bounces; this only serves to demonstrate the introspective opacity of perceptual processes. These results explain the significant drop in performance in experiment 2 when only visual period information was available, for it appears that observers were detecting a single period duration with this level of accuracy rather than detecting relative period.

Velocity. A similar result was found in the velocity condition, where the correlation between rating and elasticity \((r_m = 0.47)\) was significantly lower than that between rating and \(v_2\) \((r_m = 0.52; z_m = 0.35)\). The latter two correlations were also statistically different \((z_m = 2.05, p < 0.05)\). This pattern of results indicates that, as we had suspected from experiment 2, subjects were not detecting relative velocity information but were basing their ratings on a single rebound velocity; incident velocity did not appear to be playing a role. However, it seems that subjects were not even very accurate in detecting rebound velocity under such short exposure conditions. Debriefing results were consistent with these findings, for 67% of the subjects reported attending to the upward speed after collision. The two subjects (17%) who said they attended to the change in velocity nevertheless showed stronger correlations with return velocity.

A reanalysis of the slow velocity condition in experiment 2 (in which starting height varied widely) confirms these conclusions, and explains why performance improved somewhat in that condition. The correlation between rating and elasticity \((r_m = 0.73)\) is again significantly lower than that between rating and \(v_2\) \((r_m = 0.82; z_m = 3.22, p < 0.05)\). As in the present experiment, subjects were relying on a single rebound velocity to make their judgments of bounciness, but the improvement in the \(v_2\) correlation suggests that they were more accurate in detecting the rebound velocity with longer exposure times. Thus, even under long exposure conditions observers rely on a single rebound velocity rather than on relative velocity.

In sum, in experiment 3 we have shown the only higher-order information observers use to perceive elasticity is relative height information. Under other conditions they rely on the duration of a single period instead of relative period, but they cannot make effective use of either relative velocity or a single rebound velocity.

5 Experiment 4: auditory and visual information for elasticity

Can elasticity be perceived by ear as well as by eye? An affirmative answer was suggested in experiment 1, for there was no statistical difference between the AV condition and the auditory condition, although the trend favored the former. However, the situation is more complex than this result would indicate, for different types of information are available via the two modalities. Previous work has indicated that bouncing events can be distinguished auditorily from other classes of events such as breaking (Warren and Verbrugge 1984). In this experiment we ask some questions about the bimodal perception of elasticity in bouncing events.

A mechanical event such as the bouncing of an object may have lawful consequences in both the optical and the acoustical domains. As noted in section 1, if these optical
and acoustical patterns are unique to the event and its properties, then they constitute information that specifies the event. An observer with perceptual systems capable of detecting such patterns can thus perceive the event visually and/or auditorily. Gibson (1966) referred to such multimodally available patterns as equivalent or redundant information, and argued that, although the sensory qualities of light and sound will differ, the observer should perceive the same environmental event regardless of the modality by which the information is detected. This kind of multimodal redundancy has obvious advantages in natural situations, where any given event could be out of view or inaudible, partially obscured because of visual occlusion or noise, or visually or auditorily unattended. Alternative views suggest that the visual system tends to dominate the auditory system, or that a weighting or integration of information from different modalities is required to achieve a unitary percept. However, the information generated by natural events is typically consonant across the modalities and the problem of integrating conflicting information does not normally arise, for the optical and acoustical information are specifying the same thing. The modalities can thus be conceived as different means for detecting information about a common source event. As von Hornbostel (1927/1939) observed, "It matters little through which sense I realize that in the dark I have blundered into a pigsty" (page 210; cited in Gibson 1966, page 54).

We would like to distinguish two kinds of equivalent information across modalities. First, an event may have a variety of lawful consequences that occur together because of the mechanics of the event, but are otherwise unrelated. Gibson (1966) offered the example of a wood fire, which produces a characteristic optical pattern, acoustical pattern, chemical pattern or odor, and pattern of radiant heat; it is then an empirical question whether such information presented in each modality yields the equivalent perception of a fire. But there may also be patterns in different domains that are more formally related, in the sense that they can be given the same abstract description. We call this amodal information because the abstract pattern is not modality-specific. As pointed out by Spelke (1979), amodal information typically results from mechanical events that yield temporally synchronous optical and acoustical disturbances. In the present case, period information is produced by successive impacts of a bouncing object against the ground that yield simultaneous acoustic bursts and visible changes in the direction of motion, and the resulting pattern thus receives the same abstract description visually and auditorily [equation (6)]. We found in experiments 2 and 3 that subjects did not use relative period visually, but rather relied on single period duration. In this experiment we tested whether this is also true auditorily. A second potential source of acoustic information for elasticity is the relative intensity of successive bursts; we controlled for this in the present experiment by holding intensity constant.

This event perception view of multimodal perception leads to two predictions. First, if a given pattern can be detected both visually and auditorily, we would expect that the same amodal information presented in each modality would yield equivalent perceptual performance. Precisely this result was found by Green (to be published) for separate visual and auditory judgments of speaking rate, using the video and audio tracks from a videotape of a talker's face. Presumably, visible lip and jaw articulations and the corresponding phonetic segments occur at comparable and equally detectable rates. (We know from experience that the lack of auditory–visual synchrony in dubbed foreign language films can be quite disturbing, if not hilarious.) Similarly, Spelke (1976; 1979) found that infants as young as 4 months of age can determine which of two visible bouncing events is synchronous with or has the same period as a sequence of acoustic bursts. In the present case, if we make the same amodal information available in the visual and auditory domains, we would expect equivalent perceptual performance; thus, ratings should be based on single period duration in both modalities.
Second, if amodal information is presented simultaneously in two modalities, we would expect no improvement over unimodal presentation. Because period information is specifying the same thing in each modality separately, no new information about the source event becomes available when the optical and acoustical patterns are presented together, beyond an opportunity to catch in the second modality what one missed in the first because of inattention. Assuming adequate attention, we would thus expect no redundancy gain in a bimodal period condition over either visual or acoustic period information alone.

5.1 Method

5.1.1 Subjects. Thirty undergraduate and graduate students were paid to participate in the experiment, ten in each of the modality conditions. There were five males and five females in the auditory condition, five males and five females in the visual condition, and one male and nine females in the auditory–visual (AV) condition. None had participated in the previous experiments.

5.1.2 Displays. Displays simulating a bouncing ball were generated for three modality conditions: auditory, visual, and combined auditory and visual. In each modality there were two information conditions, a period condition with three collisions that isolated period information, and a full information condition with three to five collisions. This permitted various comparisons and controls, which we will describe below. For all conditions, display parameters were the same as those in experiment 2 ($e = 0.5$ to $0.9$, $h_1 = 4.0$ to $6.0$ m). The sound of the ball hitting the ground was represented by a low 80 ms tone, produced by iterating a 0.4 ms click at 190 Hz.

Visual conditions. The visual conditions were replications of the corresponding conditions in experiment 2. In the visual period condition the upper portion of the trajectory of the ball was masked as before and only three successive collisions were displayed on each trial. In the full visual condition the complete trajectory was visible and the number of collisions was varied randomly from three to five, hence relative height information was also available.

Auditory conditions. In the auditory period condition the presentation of the tone was timed to simulate the collisions of a bouncing ball, and only three bounces occurred on each trial. In the full auditory condition the number of bounces was varied randomly from three to five. This allowed us to control for the possibility that subjects simply rely on the total display duration, which had a higher correlation with elasticity in three-bounce displays ($r = 0.96$) than in the three-to-five bounce displays ($r = 0.81$).

Auditory–visual conditions. The AV period condition combined the visual display with the mask and the auditory display such that the tones occurred simultaneously with the visible collisions. Three collisions were presented on each trial. An improvement in this condition over visual period or auditory period alone would be evidence for a bimodal redundancy gain. The full AV condition combined the full visual display with the tones, and the number of collisions was varied randomly from three to five.

5.1.3 Procedure. Each modality condition was presented to a separate group of ten subjects, so that there was no possibility of intermodal training effects. Each subject received the period and full information conditions in a counterbalanced order, resulting in a $3 \times 2$ mixed design. Subjects were presented with four sample trials that demonstrated the endpoints of a 1 to 9 rating scale, and ten practice trials with displays from the first condition. The subsequent condition was presented with brief instructions but no further practice. There were forty-five test trials in each condition for a total of ninety trials, lasting about 20 min. Otherwise, the procedure was the same as in experiment 2.
5.2 Results and discussion

We computed correlations between bounciness rating and elasticity for each subject, and mean correlations for each condition were calculated using normalized values $z_r$ and are given in figure 6. Once again, $t$-tests on the $z_r$ in the auditory and visual conditions revealed no gender differences in performance. An analysis of variance was performed on the normalized correlations, which resulted in a significant modality effect ($F_{2,27} = 4.77, p < 0.05$), a significant effect of information (period versus full) ($F_{1,27} = 17.61; p < 0.001$), and a significant interaction ($F_{2,27} = 8.48, p < 0.01$). Comparing individual conditions, Tukey tests revealed that the full visual and full AV conditions were significantly different from the remaining four conditions (indicated by asterisks in figure 6). The differences between the full visual condition and these four conditions were significant at the $p < 0.01$ level, and the differences between the full AV condition and these four were significant at the $p < 0.05$ level; there was no difference between the full visual and full AV conditions. We will discuss these results in detail.

First, there was no statistical difference between the auditory period condition with three bounces ($r_m = 0.84$) and the full auditory condition with three to five bounces ($r_m = 0.82$). This indicates that subjects were not relying on the total display duration in their auditory judgments of bounciness. This conclusion is confirmed by the finding that the mean correlation between rating and display duration in the full auditory condition ($r_m = 0.65$) was significantly lower than that between rating and elasticity ($r_m = 0.82$), based on tests for the difference between two related $r$ for each observer ($z_m = 3.32, p < 0.001$).

Second, the significant difference between the full visual ($r_m = 0.92$) and full auditory ($r_m = 0.82$) conditions could be interpreted as a simple modality effect. However, different types of information were actually available in the two modalities: only period information in the auditory case, but both period and relative height in the visual case, with relative height yielding more accurate judgments. Controlling for this by presenting only period information in each modality, we find that the modality difference disappears, with mean correlations of 0.84 in the visual period condition and 0.84 in the auditory period condition. Thus, what initially appears to be a modality effect is actually an information effect: when information is equated, the modality difference disappears.

Third, there is no redundancy gain from making auditory period and visual period information available simultaneously, for the AV period condition also has a mean correlation of 0.84. This indicates that period information is equally accessible via

![Figure 6. Mean correlations between bounciness rating and elasticity in the auditory (A), visual (V), and combined auditory-visual (AV) conditions with period and full information in experiment 4. Asterisks indicate statistically significant differences.](image-url)
Perception of elasticity

either modality, with no additive effects. The same is true for the full information conditions, where there was no difference between the full visual condition \( r_m = 0.92 \) and the full AV condition \( r_m = 0.91 \).

In sum, the significantly higher correlations in the full visual and full AV conditions can be accounted for by the availability of relative height information in those conditions. In the other four conditions, only period information was available and performance was uniform. Thus, there was no modality effect, for when the information was equated the apparent modality difference vanished. Performance was determined by the information that was available in each modality, not by the modality per se.

These data also provide some insight into the pattern of undershooting and overshooting observed in experiment 1, for the present full AV condition is directly analogous to the AV condition in that experiment. To compare them we estimated bounce pass error from the current perceptual ratings using equations (A7) and (A8) from Appendix 1, transforming mean ratings into their corresponding elasticity values, and assuming a release height of 65 cm. Because raters in general tend to avoid using the endpoints of fixed numerical rating scales, we discarded the endpoint data. Figure 7 presents the predicted error and replots the mean error from experiment 1. Although the predicted error shows a similar pattern of undershooting at low elasticities and overshooting at high elasticities, the curve is closer to zero error—particularly over the elasticity range tested in experiment 1—and does not account for the full range of actual bounce pass error. This suggests that slight inaccuracies in perceived elasticity and insufficient adjustments of the action system both contribute to the undershooting and overshooting observed in experiment 1. However, it is worth noting that errors of 10 cm represent a misestimation of elasticity on the order of only 0.02, which is quite sensitive.

The results of this experiment lend support to the event perception view that different modalities provide different means of access to information specifying a common source event. A mechanical event that has lawful optic and acoustic consequences provides visual and auditory information that is essentially redundant. If the visual and auditory information has the same abstract description, it can be considered amodal, such as period information; on the other hand, some information may only be defined optically (such as relative height information) or acoustically, and is thus only accessible via one modality. To the extent that these optical and acoustical patterns can

![Figure 7. Mean bounce pass error in the AV condition of experiment 1 and that predicted from perceptual ratings in the full AV condition of experiment 4.](image-url)
be detected, the same environmental event is perceived, regardless of the modality by which it is perceived. By the same token, an event specified in one modality is not better specified if the same amodal information is presented in two modalities—it is still the same information, however one has access to it, and specifies the same event. Consequently, there is no redundancy gain when the same information is presented auditorily and visually. In the present case, amodal period information is available both visually and auditorily, can be detected in either modality, and yields equal performance, with no additive effects.

6 General discussion
The results of these experiments converge on three main conclusions. First, observers can accurately perceive the elasticity of a bouncing object and can use that information to control their actions. Second, they do so visually by relying on relative height information that uniquely specifies elasticity, when it is available. When relative height is not available, observers rely on the simple variable of single period duration, which does not uniquely correspond to elasticity. They appear unable to use the higher-order ratios of relative period and relative velocity, even when they think they are doing so, and do not make effective use of single rebound velocity. Third, single period duration is a source of amodal information that is equivalent for the visual and auditory modalities. Thus, human observers are capable of accurate perceptual judgments of elasticity when appropriate information is available, as Runeson (1977a) proposed for dynamic properties in general.

These results, like others in event perception, appear to be at odds with research on naive physics, which commonly demonstrates systematic misconceptions of physical principles. What might account for these divergent findings? We believe that the various experimental tasks tap at least three different sorts of knowledge and processes. First, veridical perception of a physical property or event depends on lawful relations between optical and environmental variables that are embodied in the sensitivity of the perceptual system to information. Consequently, such information may be used to control effective actions. Tasks that obtain direct judgments of environmental properties such as object motion, elasticity, mass, rigidity, or animacy as revealed in events, or require actions that depend on the perception of such properties, assess these perceptual abilities, which are the primary concern of the present study. Second, tasks in which observers judge whether an event looks physically correct or natural depend on tacit knowledge of environmental regularities—the types of events that normally occur in the natural environment. The recognition of correct trajectories in the curved-tube problem (Kaiser et al 1985), the correct water level in a tilted pitcher (Howard 1978), or anomalous pendulum frequencies (Pittenger 1986) implies this tacit knowledge, as do concrete action tasks in which such knowledge is required to produce a correct trajectory, and so on. Tacit knowledge typically cannot be verbalized—things just 'look right' or, 'feel right'—and it is predatory on veridical perception, for one cannot learn environmental regularities or actions that anticipate them if one cannot perceive them. Third, explicit conceptual knowledge may be required for cognitive tasks such as judging static representations, drawing diagrams, explicitly predicting outcomes, solving word problems, or verbalizing physics principles. Explicit knowledge may derive from perceptual experience or other sorts of instruction. Considering the ball-on-a-string problem, an observer may be able to perceive that the ball travels on a tangent when released, may be able to release the string so the ball hits a target, may be able to recognize that events with tangent paths look natural and those with curvilinear paths look wrong, or may be able to draw a diagram of the tangent path. Of course, people may possess none, some, or all of these abilities for a particular class of events—that is an empirical matter.
In a direct test of the hypothesis that cognitive tasks tap different knowledge than does the judgment of natural events, Kaiser et al. (1985) found a large improvement in performance on the curved-tube problem in both adults and children when they judged the correctness of event displays rather than static diagrams. McClosky and Kohl (1983) failed to find such an improvement in a similar experiment, but their subjects judged static diagrams after viewing moving displays of the event, instead of judging the event itself. Similar differences between word problems and static diagrams on the one hand and kinematic events on the other were found by Kaiser and Proffitt (1984) for judgments of relative mass in collision events, by Pittenger (1985) for judgments about the correctness of pendulum frequency, and by Shannon (1976) for judgments of the correct accelerative motion of bodies in free fall. These experiments lend support to the conclusion that the explicit knowledge of physics upon which cognitive tasks depend is different from both tacit knowledge of environmental regularities and the relations implicit in perceptual abilities. The evidence indicates that naive physics concepts do not mediate event perception, although they may influence performance on cognitive tasks.

However, there are also cases in which both tacit and explicit knowledge appear to be incorrect. First, McClosky and Kohl (1983) found that the naive impetus theory governed not just cognitive problem solving but also the actions of 25% of subjects in a concrete action task. These subjects tried to set a special puck on a curvilinear path by pushing it in an arc before release, when in fact it will always travel on a tangent. However, as each subject performed this unfamiliar task only once, it was clearly a predictive problem-solving task, for subjects did not have the opportunity to adjust their actions on the basis of perceptual experience with the puck. That perception itself was veridical is evident from the fact that most of them expressed surprise when, counter to their expectations, they saw that the puck did not follow a curved path upon release. Motor learning that depends on veridical perceptual experience may account for the many accurate real-world actions that are at variance with the naive impetus principle. Second, Howard (1978) demonstrated that 60% of adults exhibited no knowledge of the water-level principle when judging the naturalness of static photographs of a tilted pitcher or verbalizing the principle, and 45% similarly failed when judging films of a pitcher being tilted. However, it appears from the report that all but 1% changed their judgments after viewing a real pitcher of liquid, again suggesting that perceptual experience can modify tacit and explicit knowledge.

Finally, McClosky et al. (1983) demonstrated analogous errors in problem solving, action, and event perception tasks on the airplane problem, with 51 to 60% of subjects reporting that an object dropped from a moving carrier falls straight down rather than in a forward parabolic arc. However, the experimenters show that the moving background (the carrier) provides a perceptual frame of reference for the falling object, which is in fact moving straight down relative to the carrier, and thus perception of the trajectory is influenced by relative motion (cf. Johansson 1950). This lends support to their suggestion that certain naive physical concepts may have their origin in concrete perceptual experience with motion illusions, ‘English’ on spinning balls, and so on, in contrast to McClosky and Kohl’s (1983) converse conclusion that perception depends on naive concepts. It is important to emphasize that it is often a minority of subjects who exhibit the naive impetus theory—many subjects have abstracted Newtonian physical concepts from their perceptual experience.

Our finding that observers sometimes rely on simple rather than higher-order variables under certain conditions raises the question of the generality of these implicit perceptual relations. Under our experimental conditions, the simple variables did not uniquely correspond to elasticity because they varied as a function of both elasticity and starting height, and hence led to a decline in performance. This result is similar to that of Todd and Warren (1982), who found that visual perception of the relative mass of
two colliding objects is not based on a complex ratio of initial and final speeds that is perfectly general, but on simpler variables such as relative final speed that only correspond to relative mass over limited ranges of initial speed and elasticity. How general does a perceptual device have to be to be considered accurate? Standards for perceptual veridicality are unclear, although many researchers adopt Euclidean metrics or Newtonian physical standards when discussing perceptual error and illusions (see Shaw and Cutting 1980). However, the appropriate standards for perceptual systems that evolved to function in a terrestrial context of constraint are ecological rather than absolute: organisms only have to perceive behaviorally relevant properties over terrestrial ranges of values well enough to guide their actions and preserve their well-being (Gibson 1979). When taken outside of this natural context and confronted with novel properties, a wider range of values, or greater demands of precision, it should come as no surprise if the system performs poorly, as it is being asked to do a job it was not designed for (Runeson 1977b; Shaw et al 1981).

In the present case, perceivers may rely on limited information such as a single period duration or rebound velocity because (i) these variables are easier to detect than their general counterparts, and/or (ii) they closely correspond to elasticity under prevailing terrestrial conditions, and hence are functionally equivalent to more general information. The evolutionary trade-off between a loss of generality and the cost of building a more complex detection system is difficult to assess. But we can evaluate the second claim by calculating the correlations between elasticity and simple variables for ecologically ‘ordinary’ bouncing events, making some reasonable assumptions about initial conditions (see figure 8). Terrestrial objects do not get much bouncier than a highly elastic ‘super ball’ (\( e = 0.89 \)) and most bouncing objects in the human environment get dropped by other humans from heights of between, say, 0.2 and 2 m, although the occasional apple or fly ball may fall from up to 10 m or so. Varying \( e \) between 0.10 and 0.90 in steps of 0.05 and varying starting height between 0.2 and 2.2 m in steps of 0.1 m yields correlations between \( e \) and \( t_2 \) of \( r = 0.89 \), and between \( e \) and \( v_2 \) of \( r = 0.84 \). If we allow starting height to vary up to 10.2 m in 0.5 m steps (to keep the number of data points constant at \( N = 357 \)), the correlations drop slightly to \( r = 0.85 \) for \( t_2 \) and \( r = 0.78 \) for \( v_2 \). These figures make period duration in particular appear to be a reasonable alternative when relative height information is unavailable, as in the auditory case. This may explain why there was no significant improvement in the AV condition over the auditory condition in experiment 1: under those circumstances, single period duration correlated quite well with elasticity.

We must also be cautious in adopting the entities of classical physics as standards of veridicality (Bingham 1983; Runeson 1974). Although the intuitive properties of heaviness, bounciness, slipperiness, thickness, ‘push’, and effort have Newtonian analogues in mass, elasticity, friction, viscosity, force, and power, it is not at all clear that these are

![Figure 8. Estimated ranges of starting height and elasticity for ecological bouncing events in the space of all physically possible bouncing events.](image-url)
appropriate descriptors for behaviorally relevant properties and our perception of them. Gibson (1979) attempted a preliminary catalogue of the ecologically significant properties of objects and events and advocated the development of an *ecological physics* at the scale of organisms to replace Euclidean and Newtonian variables. A failure to find ‘accurate’ perception of physical properties may reflect inappropriate units of measurement rather than perceptual deficits. Presumably, the physical quantity of elasticity corresponds to perceived bounciness as well as it does because it captures some behaviorally relevant property of the environment, perhaps related to controlling the parameters of action. In experiment 2, bounciness ratings were linearly related to elasticity with a very strong correlation. Given the characteristics of fixed rating scales, this provides some empirical evidence that elasticity describes a perceptually significant property. If a weak or nonlinear relationship were found, we might question whether elasticity is an appropriate descriptor. Although this approach is somewhat circular, it permits empirical tests of hypotheses from ecological physics by using perceptual and motor performance as a standard for physical metrics, rather than vice versa.

In sum, we have demonstrated that observers can make accurate perceptual judgments of elasticity, that they do so by detecting relative height information visually or, if that is unavailable, a single period duration visually or auditorily. These findings lend support to the hypothesis that kinematic information is used to perceive not only spatial and temporal dimensions, but also dynamic properties of environmental events.

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APPENDIX I: Determining throw impulse from the motion of a ball

The impulse applied during a throw, including both active muscle contributions and the passive effect of gravity, can be calculated if the elasticity, release height, and final peak height are known. Working backwards from the final peak height $h_f$, the motion equation for falling bodies is

$$v_f^2 = v_2^2 + 2gh_f. \quad (A1)$$

Since final peak velocity $v_f = 0$, we can determine the rebound velocity $v_2$ as

$$-v_2 = (2gh_f)^{1/2}. \quad (A2)$$

Rebound velocity is related to incident velocity $v_i$ by way of elasticity $e$,

$$v_i = -\frac{v_2}{e}. \quad (A3)$$

Incident velocity is related to release velocity $v_r$ at height of release $h_r$ by the motion equation, and hence

$$v_r = (v_i^2 - 2gh_r)^{1/2}. \quad (A4)$$

Combining equations (A2), (A3), and (A4) we obtain

$$v_r = \left[2g\left(h_f - \frac{h_r}{e^2}\right)\right]^{1/2}. \quad (A5)$$

Finally, since impulse $I$ is equal to the change in the momentum of the ball,

$$I = m(v_r - v_o), \quad (A6)$$

and initial velocity at the peak of the throwing motion, $v_o$ is 0, then substituting equation (A5) into equation (A6) we obtain

$$I = m\left[2g\left(h_f - \frac{h_r}{e^2}\right)\right]^{1/2}. \quad (A7)$$

This can also be rearranged to predict final peak height as a function of action parameters

$$h_f = e^2\left(h_r + \frac{I^2}{2gm^2}\right). \quad (A8)$$
APPENDIX 2: Derivation of information specifying elasticity

The coefficient of restitution $e$ is defined in terms of the observable motions of two colliding bodies having velocities $v_1$, $v'_1$ before collision and $v_2$, $v'_2$ after collision. The coefficient is defined as the ratio of the difference in velocities after collision to that before collision,

$$ e = \frac{v'_2 - v_2}{v_1 - v'_1}. \quad (A9) $$

In the case of a bouncing ball, the earth is so massive as to be effectively stationary, so that $v'_1 = v' = 0$. Thus,

$$ e = -\frac{v_2}{v_1}, \quad (A10) $$

which constitutes relative velocity information.

To derive relative height information, consider that the rebound velocity $-v_2$ determines the subsequent peak height $h$ by the motion equation (A2). Since the rebound velocity is equal to the next incident velocity when the ball returns to earth, we can substitute equation (A2) into equation (A10) for two successive peak heights, obtaining relative height information,

$$ e = \frac{(2gh_2)^{1/2}}{(2gh_1)^{1/2}} = \left(\frac{h_2}{h_1}\right)^{1/2}. \quad (A11) $$

To derive relative period information, consider that one half-period is equal to the time required for the ball to decelerate from its rebound velocity $-v_2$ to rest at peak height (or, equivalently, to fall back to earth). This half-cycle time $t = \frac{1}{2} \tau$ is related to rebound (or the next incident) velocity by $v = gt$, so that

$$ -v_2 = \frac{1}{2} \tau g. \quad (A12) $$

Substituting this into equation (A10) for two successive periods, we obtain relative period information

$$ e = \frac{\frac{1}{2} \tau_2 g}{\frac{1}{2} \tau_1 g} = \frac{\tau_2}{\tau_1}. \quad (A13) $$