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Influence of Animation on Dynamical Judgments

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The motions of objects in the environment reflect underlying dynamical constraints and regularities. The conditions under which people are sensitive to natural dynamics are considered. In particular, the article considers what determines whether observers can distinguish canonical and anomalous dynamics when viewing ongoing events. The extent to which such perceptual appreciations are integrated with and influence common-sense reasoning about mechanical events is examined. It is concluded that animation evokes accurate dynamical intuitions when there is only 1 dimension of information that is of dynamical relevance. This advantage is lost when the observed motion reflects higher dimension dynamics or when the kinematic information is removed or degraded.

In the past decade, cognitive scientists have focused a good deal of attention on people's understanding of physical systems. Given that most physical systems behave deterministically, it is reasonable to ask to what extent people recognize these regularities, notice deviations from the natural course of events, and have internalized these regularities into their reasoning about the systems. Our own work has concentrated on people's perceptual and conceptual understandings of mechanics. This work was motivated by two concurrent developments in the literature. The first, emerging from the domain of event perception, was the suggestion that dynamical information is carried in the optical array. The second, emerging from cognitive psychology, was the finding that many well-educated people are unable to produce correct answers to seemingly trivial physics problems.

In this article, we discuss the special perceptual status of classical mechanics as a domain within physics. We then consider an account of dynamical event complexity provided by classical mechanics, together with its implications for perceiving dynamical events. We empirically demonstrate that people's ability to appreciate the natural dynamics of ongoing events is limited by the complexity of the mechanical system. Finally, we consider the implications of our findings for theories of intuitive physics and how animation can be used to enhance people's spontaneous understandings of physical systems.

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Why Mechanics?

Physics is traditionally divided into four major branches: classical mechanics, electrodynamics, thermodynamics, and quantum mechanics. Classical mechanics is the oldest branch of physics, dating back at least to the time of Aristotle.[1] The basis of its historical precedence coincides with our interest as perceptual psychologists: Mechanics is about the motion of rigid bodies that can be seen. Mechanical systems were the first studied because they are the most obvious. In the other major branches of physics, the individual motions of the relevant particles are invisible. Understanding of these systems is built on either pure formalisms or through analogy to visible systems (e.g., Gentner & Gentner, 1983).

Because the relevant elements of mechanical systems are perceptually available for casual inspection, people find it a natural task to be asked to reason about their dynamics in an informal context. Thus, whereas it is possible to study response protocols of subjects solving formal physics problems in electrodynamics, thermodynamics, or quantum mechanics (e.g., Chi, Feltovich, & Glaser, 1981; Simon & Simon, 1978), simple problems of mechanics lend themselves to the study of intuitive understandings in ways that these other physical domains do not: Understanding in the domain of classical mechanics can, in principle, be based on perceptual experiences.

Our study of people's understanding of mechanics was energized by two intriguing contributions that appeared about a decade ago. The first was Runeson's (1977) thesis demonstrating that it was possible in principle to extract dynamic information from the kinematics of some simple mechanical events. The second was a series of demonstrations by McCloskey and his colleagues that many college-age subjects, even after formal coursework in physics, held striking misconceptions about the outcome of simple mechanical events

[1] Although some scientific historians cite earlier Egyptian and Babylonian roots, most agree that Aristotle's *Physics* founded the academic subject of physics in the 4th century B.C. This essay served as the cornerstone for Western scientific thought until the Renaissance.

(Caramazza, McCloskey, & Green, 1981; McCloskey, 1983a; McCloskey, Caramazza, & Green, 1980). The juxtaposition of these findings struck us as somewhat paradoxical: If we actually perceive mechanical forces in our environment, why then do we demonstrate such poor understanding of the outcome of these forces when asked to reason about them on seemingly trivial problems? Furthermore, given that we give erroneous predictions about these mechanical systems, would we regard these anomalous motions as being natural outcomes when viewing simulations of these events? Or would animation evoke more accurate dynamical judgments? We suggest that the answer to this final question is both yes and no. Animation allows people to appreciate natural outcomes in some motion contexts, but not in others. The delineation of these motion contexts is drawn from the taxonomy of dynamical event complexity detailed in Proffitt and Gilden (1989); what follows is a brief summary.

Motion Complexity: Particle Versus Extended-Body Systems

A mechanical system is a collection of objects moving under the action of external and internal forces. There exists a definite limit to the simplicity of mechanical systems. This limit defines two categories of dynamical events: particle motions and extended-body motions. These two classes of events are distinguished by the number of object descriptors that are effective variables within the dynamical system in which the object is observed. In particle motions, only one object dimension is dynamically relevant. Extended-body-motion contexts make relevant additional object descriptors such as mass distribution, size, and orientation. The definition does not depend on whether the object is a particle; rather, it depends on the dynamical system in which the object is observed. Although this account is defined in physical terms, it is not simply the transportation of a conventional distinction taken from physics into cognitive psychology. Our distinction is about problem representations; that is, in looking at the equations that represent a dynamical system, we ask how many object dimensions are effective, one or more than one. These dimensions are defined by physics and provide an ideal competence theory to which human performance theories can be related.

First, consider rigid object motions and the two contexts shown in Figure 1 for the motion of a top: (a) free fall of a top that has been dropped in a gravitational field (assume a vacuum) and (b) precession of a spinning top that is balanced on a pedestal in a gravitational field. Both are examples of a top falling, but the two motions are quite different, as are the properties of the top that are of dynamical relevance. For example, the shape of the top only matters if a torque is applied to it. The motion of the center of mass of a spinning top in free fall is identical to that of a nonspinning one. In this context, its trajectory is straight down with the velocity, v, defined by

$$v = (2dg)^{1/2}, \qquad (1)$$

where d is the distance fallen, and g is acceleration due to gravity. On the other hand, a spinning top that is supported by a pedestal is subject to a gravitational torque about the point of contact. In this situation, spinning is relevant to the top's behavior. A nonspinning top falls down, and a spinning top falls sideways (i.e., it precesses). A top spinning on a pedestal has many more dynamically relevant dimensions as is revealed by the equation for the angular velocity of its precession, ω_p:

$$\omega_p = (rMg)/(I\omega_r), \qquad (2)$$

where r is the distance of the top's center of mass to the pedestal, M is the top's mass, I is the top's moment of inertia (an object descriptor that is a function of the top's mass distribution), and ω_r is the top's angular velocity around its primary axis.

Consider next the domain of fluid statics: the determination of how much fluid is displaced by an object placed within it. Archimedes's principle states that the buoyant force of a body is equivalent to the weight of the fluid that it displaces. Whether an object floats is determined by its density in relation to the liquid in which it is placed. For a floating object, its mass determines the amount of liquid that is displaced. For a sunken object, displacement is determined by volume conservation. In general, liquid displacements are

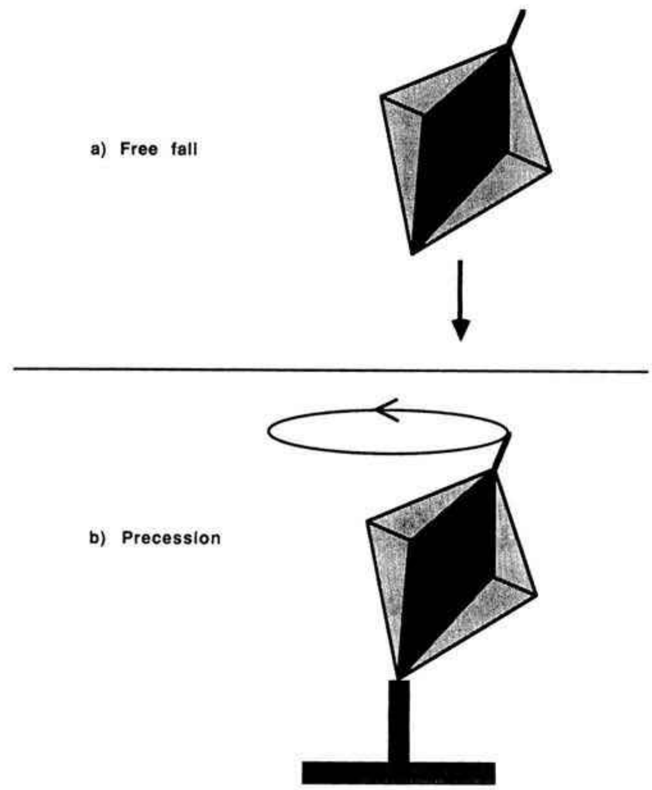

Figure 1. Two motion contexts for a spinning top. (Panel a shows the top in free fall. In this context, no attribute of the top affects its velocity. A free-fall context permits all objects to be regarded as extensionless point particles located at their center of mass. Panel b shows the spinning top precesses. In this context, information about mass distribution and angular velocity are required to describe the object's dynamics adequately.)

extended-body systems because there are two object descriptors in their problem representations that are dynamically relevant: mass and volume. These dimensions combine to define object density. Relating this density to that of the liquid determines the state of the object (floating or sunken); this state determines which object variable (mass or volume) is the effective one. Note, however, that if the state of the object is already known, the problem representation then becomes unidimensional, meaning that only one object descriptor is relevant to the system's dynamics. We refer to such constrained representations as *one-dimensional slices of extended-body systems.*

Dynamical analyses of particle motions (and one-dimensional slices of extended-body systems) are much simpler than are those of unconstrained extended-body motions. This is due to the increased number of parameters that must be included in an adequate dynamical representation of extended-body systems. Particle motions can always be understood in terms of center-of-mass displacements; one-dimensional slices of extended-body systems have but one effective object descriptor as well. Dynamical representations of extended-body motions always relate more than one category of information. In extended-body motions, it is not sufficient to rely on a single object dimension. The relating of different categories of information must be performed through multiplicative processes, and it results in multidimensional quantities that are not categories of perception (Proffitt & Gilden, 1989).

Animation's Influence on Dynamical Judgments in Particle and Extended-Body Events

We propose that the complexity of the motion system under observation has important implications for the efficacy of animation in aiding dynamical judgments. Specifically, we propose that animation allows people to make accurate naturalness judgments in particle-motion contexts but not in most extended-body situations. This is because in particle-motion contexts, animations provide all of the necessary information about the motion state. Thus, the very act of looking at an object in a particle-motion context is simultaneous with noticing the single dimension that is of dynamical relevance: the position over time of the object's center of mass. When additional motion parameters must be considered for an adequate dynamical analysis, as is the case for extended-body systems, our perceptual processing of the event is not adequate.

Furthermore, animation serves to segregate in time changes in the dimensionality of an object's motion (i.e., its *dimension state*). This aids observers in appreciating when an object undergoes a transition from an extended-body to a particle-motion system, as, for example, when the bob of a pendulum is severed. Before the sever, the bob is part of an extended-body pendulum system; after the sever, its dynamics are appropriately characterized as being particulate. This temporal parsing can also aid observers in certain extended-body problems, but only those in which the problem space has been constrained to a region in which a single object parameter is of dynamical significance (i.e., a one-dimensional slice).

In general, then, we propose the following framework for when and how animation aids dynamical judgments. People are able to make fairly accurate dynamical judgments about particle systems and one-dimensional slices of extended-body systems when the systems are properly construed as such. Animation can assist people in making this assessment about objects' motions and dimensional states. Intuitions concerning extended-body systems are usually poor; only when dealing with a one-dimensional slice through the problem space do people demonstrate reasonable levels of competence. Animation can aid in this context by temporally parsing a multidimensional problem into unidimensional components.

Evidence That Animation Does Not Evoke Accurate Dynamical Judgments About Extended-Body Systems

We and others have found that animation does not aid people's naturalness judgments on most extended-body-motion problems. For example, in one study (Proffitt, Kaiser, & Whelan, 1990), we showed subjects computer animations of rotating satellites. From an initial constant angular velocity, the satellite changed its configuration by extending or contracting the solar panels of which it was composed. These extensions–contractions resulted in changes in the mass distribution of the satellite and, in nature, would cause corresponding changes in angular velocity; when the mass distribution moves closer to the axis of rotation, the angular velocity must become greater to maintain a constant angular momentum. We found that subjects demonstrated virtually no appreciation for whether these events reflected natural dynamics. The only animations judged to look anomalous were those in which the extension or contraction resulted in the satellite either stopping or stopping and reversing direction of spin.

Similarly, Howard (1978) and McAfee and Proffitt (1991) found that animation does not aid people's performance on the water-level problem. In the paper-and-pencil version of this problem, people are asked to describe (or draw) the surface orientation of a liquid when its container is tilted. Very commonly, people fail to report that the surface orientation remains invariantly horizontal, regardless of container orientation. In the animated context, people were shown events in which a glass was tilted from upright, and they were asked to judge whether the water level moved in a natural manner. Generally, people did not perform better on this task than on the static tasks. The anomalous outcomes were not perceived as such. Perception did not penetrate this extended-body motion.

Evidence That Animation Evokes Accurate Dynamical Judgments About Particle Systems

Such failures of animation to evoke accurate naturalness judgments for these extended-body problems stand in stark contrast to work involving particle-system problems. The problems that we have studied in this domain were taken from those used by McCloskey and his colleagues and are of interest because people fail on them in static contexts. Usually, these problems are presented in the intuitive physics literature as representing extremely simple motion problems, and it is true that they are particle-motion problems. These problems, however, also represent some of the most difficult cases of particle motion because the problems often involve situations in which the object is initially construed as being part of an extended-body system, and then something happens that places it in a particle-motion system. Thus, for example, people are asked to predict the trajectory that a pendulum bob takes when the cord connecting it to its pivot is severed. While the bob is connected to its pivot, it is part of an extended-body system. Once severed, the bob undergoes free fall and thus is adequately described as a point particle.[2] People must recognize the dynamical significance of the transition that occurs when the bob is severed. Although this realization is difficult to intuit in static contexts, the change from an extended-body motion to a particle motion is apparent in animation. This, as we have proposed, is the second way in which animation facilitates naturalness judgments: Animation segregates in time changes in the object's dimension state.

In an initial examination of animation efficacy, we conducted a study that compared people's ability to recognize the natural outcome of a simple trajectory problem in static and dynamic contexts (Kaiser, Proffitt, & Anderson, 1985). We chose the C-shaped-tube problem for this study. In this problem, people are asked to predict the trajectory a ball would take upon exiting a curved tube lying on a flat surface (e.g., a table top). Like the pendulum problem described earlier, this curved-tube problem involves a transition from an extended-body system (when the ball is in the tube) to a particle system (when the ball exits the tube).[3]

When McCloskey et al. (1980) administered this problem in a paper-and-pencil format to college students, about a third of the students responded that the ball would continue to follow a curved trajectory once outside the tube. In our study, we first replicated McCloskey et al.'s (1980) findings with a free production task as they did and then extended it to a forced-choice paradigm. (This manipulation was necessary because we needed to show alternative trajectories in the animation condition. Thus, we needed to verify that people made errors in a static forced-choice context.)

What we found in our animation condition was quite striking. The people who selected a curvilinear trajectory in the static task rejected this trajectory in the animation task in favor of the correct trajectory. Animation permitted the subject to see the motion state of the ball once it exited the tube. Furthermore, the animation temporally segregated the epoch in which the ball participated in an extended-body system (in the tube) from that in which it behaved as a point particle (upon exiting the tube). This temporal parsing made the transition in the dimensional state apparent to the subject. The specification of motion state and dimensional state allowed subjects to recognize the natural outcome in the animated condition. These states were difficult to intuit in a static context, even when the animated display had been shown just minutes before; subjects who performed the static task after the animated task were just as prone to error as those who performed the static task first. Nor were people readily able to mentally evoke the dynamical information carried in the animation; instructions to subjects to create moving mental images of the event did not improve performance on the static task.

We propose that classical mechanics provide a framework of motion complexity with important implications for the perceptual penetration of natural dynamics. In particular systems, which can be adequately described by the most simplified laws of motion, people can appreciate natural dynamics when viewing ongoing events because the perceptual system inherently attends to the motion of objects' configural centroids (Proffitt & Cutting, 1980). For objects of uniform density, this centroid coincides with the object's center of mass, whose motion is the only parameter of dynamical relevance for a particle system. In cases of higher motion complexity, higher order quantities are usually required to describe the dynamics. Because the visual system is incapable of extracting these multidimensional quantities, the dynamics of such extended-body systems are perceptually impenetrable. Thus, people should demonstrate the ability to recognize natural dynamics either when viewing motions adequately characterized by particle dynamics, or when viewing motions specifying subspaces of extended-body systems in which only a single parameter is dynamically deterministic.

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[2] A simple pendulum consists of a bob suspended by a string that is attached to a pivot. The bob behaves like a particle; its mass distribution, size, and other physical characteristics are not dynamically relevant. If one assumes that the string is massless, the simple pendulum's motions are governed by the general equation of rotational motion: $\tau = I\alpha$, where τ is torque, I is moment of inertia, and α is angular acceleration. Moment of inertia is $I = ml^2$, where m is the mass of the bob and l is the length of the string. Although the bob itself is treated as a particle by the pendulum system, its distance from the axis is an object descriptor of dynamical relevance. Thus, the motions of simple pendula have two effective variables: the amplitude of the oscillation and the length (l) of the string. (This is not to say that both of these variables are effective in determining all aspects of pendular motions. Both frequency and periodicity are independent of amplitude.)

[3] The motion of a ball rolling through a C-shaped tube is a particle motion if the ball's spin is ignored and is an extended-body motion if spin is taken into account. Because many subjects interviewed after completion of the C-shaped-tube task spontaneously stated that the ball's exit trajectory will be affected by the spin that it acquired while in the tube, we described C-shaped-tube contexts generally as being extended-body systems. As it rolls through the tube, the ball will acquire a spin that is influenced by the internal curvature of the tube's walls. For vertical walls, the ball's spin will be around an axis that is perpendicular to the rolling surface. Such a spin is called English in pool and will not influence the trajectory of the ball upon exiting the tube. It will, however, influence the trajectory of the ball following a collision involving significant friction. If the curvature of the tube's wall is such that the ball makes contact with the wall's surface between the horizontal rolling surface and the ball's horizontal equator, then the ball will acquire a spin that is not around an axis orthogonal to the rolling surface. This spin will cause the ball's exiting trajectory to curve in a direction opposite the curvature of the C-shaped tube.

Overview to the Experiments

In the following three experiments, we investigated whether dynamical judgments for three motion problems were aided by animation, as would be predicted by our account. All three problems have been studied extensively in a static context and have been found to evoke errors in that context. The first problem we examined is the pendulum problem. Here, people were asked to predict the trajectory a pendulum bob takes if its tether is severed at various points in the trajectory. Like the C-shaped-tube problem, the pendulum problem involves the transition of an object from an extended-body system to a particle-motion context. We predicted that animation would enable subjects to appreciate the bob's motion state as well as this transition in dimension state and to recognize the natural dynamics specified by the bob's center of mass kinematics in its particle-motion (postsever) state.

The second experiment involved the problem of an object dropped from a moving carrier. In a static context, people often report the object's motion in relation to the carrier as its absolute motion. We predicted that in an animated context, the natural motion state of the object's center of mass will be apparent, independent of whether observers adopt an environment-relative or carrier-relative frame of reference.

Our final experiment examined the efficacy of animation for evaluating one-dimensional slices of an extended-body system. Our framework suggests that within such subspaces, animation can aid dynamical judgments. We have chosen the domain of fluid displacements because as was discussed earlier, there are subspaces of the problem in which displacement is predicted by a single dimension. Animation should serve to parse multidimensional displacement problems into its unidimensional problem components. In the absence of animation, people's understanding of the problem should be muddled for multidimensional problems yet remain competent within the one-dimensional slices.

As a body, these experiments were designed to provide support for our account of the conditions under which animation will and will not aid subjects' dynamical judgments.

Experiment 1: The Pendulum Problem

A pendulum is an extended-body system. The motion of the pendulum bob is determined by the length of the cord connecting it to the pivot and the angular displacement of the cord from the gravitational vertical. If, however, the cord connecting the bob to the pivot is severed, the bob's motion can now be fully described within a particle-motion context. If the sever is made with the bob at its apex, the bob has no horizontal velocity and behaves as any object dropped from a position at rest; if severed at its nadir, the bob has a horizontal velocity component in addition to the vertical acceleration and thus traces a parabolic trajectory.

Caramazza et al. (1981) asked college students to reason about this pendulum problem in a static context. Subjects were shown drawings of pendulum systems at four points in the harmonic cycle (i.e., the nadir, the apex, and two points in between) and were asked to draw the trajectory the bob would take if the cord were severed at each of these four locations. Only a quarter of the subjects produced correct responses for all four problems. Caramazza et al. concluded that "simple real-world experience with moving objects does not lead naturally to the abstraction of principles that are consistent with the formal laws of motion" (p. 121).

Our interest was to determine whether people are able to make accurate naturalness judgments when viewing animations of these severed-pendulum-bob events. We predicted that subjects could recognize the natural outcome because animation provides all the necessary information about the motion state of the bob when it is in its postsever, point particle context. Furthermore, animation serves to segregate in time the change in the dimensional state of the bob's motion from an extended-body to point particle context.

We conducted two studies on the pendulum problem. In the first, we attempted to replicate the Caramazza et al. findings and examined whether people would make the same errors if the task were to choose the correct trajectory from a number of alternatives rather than to produce a trajectory drawing. As with the C-shaped-tube problem, this extension was necessary because it was not possible to create an animation production task; thus, we needed to have a forced-choice assessment in a static context. If subjects still erred on the static forced-choice task, we could then examine whether performance was better for an animated forced-choice task.

Experiment 1A: Free-Hand and Forced-Choice Static Pendulum Problem

Because Caramazza et al.'s study used a production task, we conducted this initial study to verify that people would make similar errors in a forced-choice paradigm. This would allow us to create animated and static trajectory exemplars for a subsequent forced-choice study.

Method

Subjects. Eighty University of Virginia undergraduates (40 men and 40 women) participated in this study for course credit. Thirty-two of the men and 31 of the women had taken physics courses in high school, college, or both.

Procedure. Subjects were administered a free-hand drawing task in which they were asked to predict the trajectory a pendulum bob would take if the cord connecting it to the pivot were severed at the apex and at the nadir. They also participated in a forced-choice task in which all pairs of five trajectory alternatives were presented. The alternatives we used were representative of the responses given to a free production task reported in Caramazza et al. The top half of Figure 2 shows the alternatives for the apex problem; the bottom half of Figure 2 has the nadir alternatives. In the apex problem, the natural trajectory is Alternative 1; at its apex, the bob has no horizontal velocity, so it falls straight down when severed. The correct alternative for the nadir problem is 2. Although it is impossible to determine the exact shape of the bob's trajectory without knowing the physical scale of the depicted system (to determine the bob's horizontal velocity in relation to the gravitational component), the natural outcome would trace some sort of parabolic path, and Alternative 2 is the only member of that family.

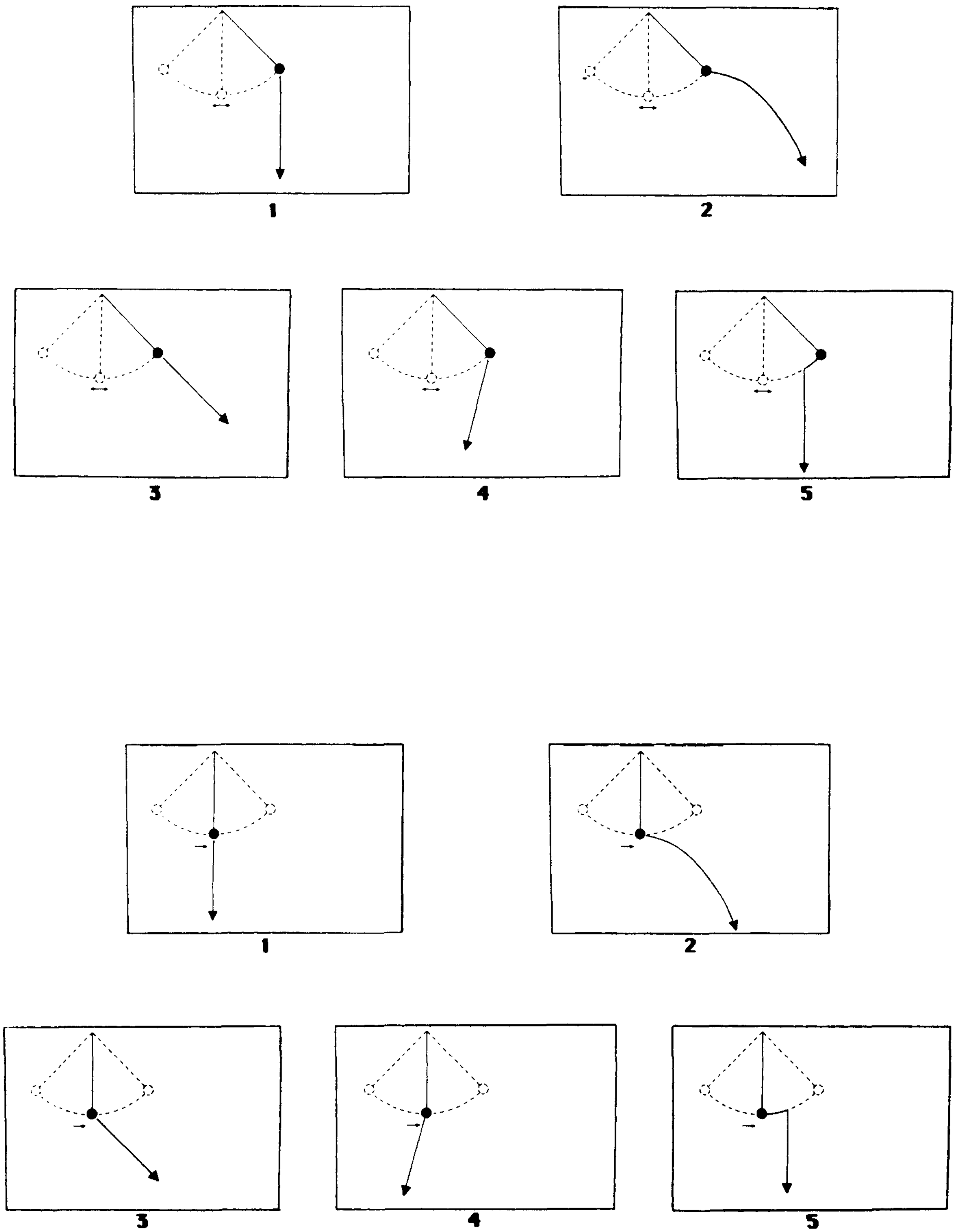

Figure 2. The five trajectory alternatives for the apex (top) and nadir (bottom) pendulum problems in Experiment 1. (Trajectory 1 is the natural outcome for the apex problem; Trajectory 2 is the natural outcome for the nadir problem.)

The stimuli were presented in test booklets, with one pair on each page. Subjects were instructed to indicate which trajectory of the pair was closer to the natural outcome and then to proceed to the next page. The order in which the free-hand and forced-choice tasks were administered was counterbalanced across subjects; half drew trajectories first, and half chose first.

Results

Subjects' free-hand drawings were categorized into one of the five alternatives by two judges. The two judges made consistent assignment to a category for 73% of the drawings. The paired-comparison data were analyzed two ways. First, to facilitate comparison with their free-hand drawings, each subject's most preferred trajectory for the apex and nadir problems was determined. Only those subjects whose preferences demonstrated consistency were considered. Preferences were deemed consistent if there was no more than one circular triad among the pairs (a circular triad occurs when, for example, Trajectory 1 is preferred over 2, 2 over 3, but 3 over 1; for further discussion, see Coombs, 1964). Consistent preference for a trajectory alternative was shown 71% of the time. The proportions of codable responses that produced or selected correct responses are shown in Table 1, together with the free-hand drawing data from the Caramazza et al. (1981) study.

Subjects in our study performed similarly to those in Caramazza et al.'s (1981) for the apex problem. Only a third of the subjects drew and only a quarter chose the correct response; the majority of incorrect responses predicted a parabolic path. Our subjects performed better on the nadir problem. More than half drew the correct parabolic path and 81% chose it as the preferred trajectory. Across the two problems, proportion of correct–incorrect responses did not differ as a function of task format (i.e., free-hand production vs. forced choice). No effect was noted for either order of task presentation or whether subjects had taken courses in physics.

Significant gender effects were found for both tasks. More men drew correct trajectories for both the apex problem (16 men vs. 3 women), $\chi^2(1, N = 58) = 8.89, p < .01$, and the nadir problem (25 men vs. 7 women), $\chi^2(1, N = 58) = 10.12, p < .01$. Similarly, more men demonstrated a preference for the correct apex trajectory (12 men vs. 1 woman), $\chi^2(1, N = 57) = 9.31, p < .01$, and the correct nadir trajectory (33 men vs. 15 women), $\chi^2(1, N = 57) = 6.75, p < .01$, in the forced-choice task.

Table 1
Proportion of Subjects Who Drew or Consistently Chose the Correct Trajectory for the Apex and Nadir Pendulum Problems

Problem type	Caramazza, McCloskey, and Green's (1981) free-hand task	Free-hand task	Forced-choice task
Apex	.32	.33	.23
Nadir	.25	.55	.84

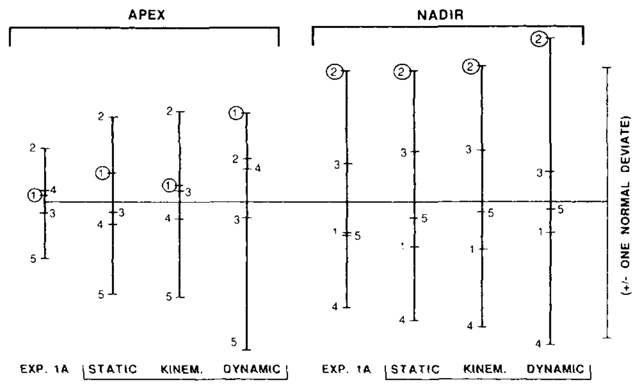

Figure 3. Thurstonian Case V scaling solutions for the preference data from Experiments 1A and 1B. (Alternative 1 is the canonical outcome for the apex problem; Alternative 2 is the canonical outcome for the nadir problem.)

The paired-comparison data were also used to construct Thurstonian Case V scaling solutions of subjects' preferences among the five alternatives (Torgerson, 1958).[4] As shown in Figure 3, subjects' preferences on the apex problem demonstrated a relatively small discrimination range (less than one normal deviation), and the erroneous parabolic trajectory is most preferred; the correct trajectory is the third most preferred. For the nadir problem, the correct trajectory is most preferred and fairly well discriminated from the erroneous foils. More will be said about these scaling solutions in comparison to the data from Experiment 1B.

Experiment 1B: Static, Kinematic, and Dynamic Pendulum Problems

Given that people demonstrated similar performance on free-hand production and forced-choice tasks, we were able to use a forced-choice paradigm to examine the impact of animation on subjects' dynamical judgments.

Method

Subjects. Forty-eight University of Virginia undergraduates (24 men and 24 women) participated in this study. None had participated in Experiment 1. Although no data were collected on subjects' physics training, this sample was drawn from the same population as Experiment 1 and most likely had similar physics training (i.e., high school or college coursework).

Stimuli. All stimuli were shown on a 114.3-cm diagonal rear projection video screen to subjects in groups of 3 or 4. Three types

[4] Thurstonian Case V scale solutions were constructed both including and deleting the preference data from subjects who demonstrated inconsistencies. The solutions were virtually identical. The solutions reported here and for the following experiments used the preference data from all subjects.

of stimuli were used: static, kinematic, and dynamic. The kinematic stimuli contained some motion information (i.e., the trajectories were drawn in real time) but did not reflect veridical dynamics. In these displays, the initial image was the same as in the static condition. The only difference was that the line depicting the falling trajectory was drawn with a constant velocity (i.e., pixels per frame) rather than appearing all at once. If motion per se is sufficient to engage people's appreciation of natural dynamics, then performance in this kinematic condition should resemble that with the dynamic stimuli. These kinematic stimuli failed to specify adequately the motion state of the bob. Furthermore, by failing to show any motion in the pendulum system or the transition in motion state, these stimuli may have been insufficient to make the dimensional state transition from extended body to particle system salient. Thus, for example, the transition from no horizontal motion to some horizontal motion was absent for the apex problem foils.

The static stimuli were similar to those used in Experiment 1A's forced-choice task, with the following changes: (a) Whereas the two alternatives of each pair were shown side by side in the test booklet, here they were shown sequentially; (b) instead of the unlimited viewing period allowed for the test booklets, each alternative was displayed for a fixed interval corresponding to the event time in the animated stimulus condition; (c) the orientation of the display was consistent with gravity (most subjects had laid the test booklet on a desk in the first experiment, placing the pendulum system orthogonal to its natural environmental orientation); (d) a human figure was added to specify the scale of the system (the tether's length was approximately one and a half times the figure's height). For the kinematic stimuli, the same depiction of the pendulum system was used as in the static stimuli. Once the connecting cord was severed, however, the trajectory was drawn in real time, at a constant velocity.

The dynamic stimuli showed the pendulum swing for two full cycles. During the third cycle, the connecting cord was severed when the bob reached either its apex or nadir. The bob then moved along one of the five trajectories, with the constraints that all trajectories depicted an identical, scale-appropriate gravitational acceleration, and changes in velocity and direction in the anomalous trajectories were ramped to minimize abrupt motion transitions.

Procedure. For all three stimulus conditions, subjects were shown all possible pairs of the five trajectory alternatives and asked to judge which appeared more natural, or closer to a possible outcome. Half of the subjects saw the displays in the following order: dynamic stimuli (apex problem first, followed by the nadir problem), kinematic stimuli (apex and nadir), and static stimuli (apex and nadir). The other subjects saw static stimuli (nadir and apex), kinematic stimuli (nadir and apex), and dynamic stimuli (nadir and apex). As in our C-shaped-tube study, we used a within-subjects design to assess whether order effects would occur. In particular, if performance was better with the dynamic stimuli, would subjects' performance on the static task be better if they had already judged the dynamic stimuli? Our design allowed us to access whether a person's ability to judge the naturalness of a trajectory in a static context benefited from recent exposure to the event in a dynamic context.

Results

Subjects' preference data were analyzed in two ways. First, we conducted a univariate repeated measures analysis of variance (ANOVA) by using simply the number of times the subject selected the correct trajectory (out of a possible four) as the dependent variable. This analysis had two grouping variables (gender and order) and two within-subjects variables: stimulus condition (dynamic, kinematic, and static), and problem (apex and nadir). For the apex problem, planned comparisons revealed that subjects chose the correct trajectory significantly more often in the dynamic stimulus condition ($M = 3.00$) than when viewing the kinematic ($M = 2.21$) or static ($M = 2.29$) stimuli: $F(1, 45) = 6.64$, $p < .001$. As in Experiment 1A, subjects did well on the nadir problem in all conditions (dynamic $M = 3.65$; kinematic $M = 3.54$; static $M = 3.50$), such that the effect for the dynamic stimuli did not reach significance, $F(1, 45) = 2.27$, $p < .10$.

Performance was not affected by task order, $F(1, 45) = 0.06$, *ns*; thus, having chosen the correct trajectory in the dynamic stimulus condition did not aid performance on the static or kinematic stimulus conditions. Gender effects were noted in the static and kinematic stimulus conditions, with men choosing the correct trajectory more often than women. In the static stimulus conditions, men chose the correct trajectory an average of 3.18 times compared with 2.60 for women, $F(1, 45) = 9.72$, $p < .003$. For the kinematic stimuli, the averages were 3.10 for men and 2.64 for women, $F(1, 45) = 5.61$, $p < .02$. We found no gender difference in the dynamic stimulus condition, however; men averaged 3.36 correct choices, and women averaged 3.21, $F(1, 45) = 0.96$, *ns*.

We then used the full-preference data sets to construct Thurstonian Case V scaling solutions for the six cases defined by problem type (apex or nadir) and stimulus condition (static, kinematic, or dynamic). The scaling solutions are shown in Figure 3, along with the solutions for the preference data from Experiment 1A. Two important aspects of these scales should be examined: the relative preference rankings of the alternatives and the scale distance among the alternatives (which is indicative of the degree of discriminability).

For the apex problem, the correct trajectory is the most preferred alternative in the dynamic condition only. The erroneous parabolic trajectory is most preferred in the static and kinematic conditions (and was most preferred in Experiment 1A). In addition, the scaling solution for the dynamic condition demonstrates a greater degree of discrimination among the alternatives. The dynamic condition scale spans 1.56 normal deviations (nd). The spans of the scales for the static and kinematic conditions are 1.31 and 1.39 nd, respectively. The scale of Experiment 1A preference data has the smallest range, spanning only 0.81 nd.

The scaling solutions for the nadir problem are qualitatively similar for all conditions in this experiment and for the data from Experiment 1A. All four scales have the correct trajectory (Alternative 2) as the most preferred alternative, and the rankings of the other four alternatives are similar. As with the apex preference data, the greatest discriminability is shown in the dynamic condition scale (range = 2.27 nd), followed by the kinematic and static conditions (range = 1.94 and 1.84 nd, respectively). Again, the scale of Experiment 1A's data has the most limited range, but it still spanned 1.72 nd.

Discussion

The findings of these experiments bear a striking resemblance to our earlier findings for the C-shaped-tube problem (Kaiser, Proffitt & Anderson, 1985). First, Experiment 1A demonstrated that people make the same kinds of errors on free-hand production tasks as they do in a forced-choice paradigm. This suggests that production deficiencies (Flavell, 1977) are not the basis of their failure on these problems of mechanical intuition. Second, men tend to perform better than women when the problems were presented in nondynamic formats; similar gender effects were noted with adults on the C-shaped-tube problem.

Most critically, Experiment 1B demonstrates that both men and women do well on the problems when asked to solve them in an animated context. This competence is limited to the full dynamical simulation; solutions recognized in this context are not then generalized to problems subsequently presented in static formats. In addition, it appears that the dynamics must be canonically instantiated in the animations. The presence of motion per se (as in the kinematic condition in Experiment 1B) or instructions to imagine the motion event (as used in Kaiser, Proffitt, & Anderson, 1985) does not seem sufficient to evoke accurate dynamical intuitions. Other research (M. Rudisill, personal communication, May 1989) has also found that animations lacking canonical dynamics fail to elicit any better performance than static representations. The alternative discriminability was slightly better in the static and kinematic conditions of Experiment 1B than in Experiment 1A. This difference could merely reflect variation in the subject population, or it could suggest that changes in the problem presentation (e.g., orienting the display consistent with gravity) enhance performance.

According to our framework, animation provides two critical sources of information concerning these problems. First, it serves to specify the motion state of the object at every instant in the event. Thus, for the apex pendulum problem, animation allows one to see that the bob has no horizontal velocity at the instant that the tether breaks. Just as everyone realizes that an object released from a stationary point will fall straight down (Kaiser, Proffitt, & McCloskey, 1985), so too do they recognize that this is the natural outcome for the bob released at this point. As our findings from the kinematic stimulus condition demonstrate, it is this specification of the motion state, not the presence of motion per se, that allows subjects to appreciate the canonical outcomes of events. Second, animation temporally parses the event's two dimension-state epochs: the interval in which the object (the ball in the C-shaped tube or the bob in the pendulum) is part of an extended-body system and the interval in which it is in a particle-motion context.

Experiment 2: The Object Dropped From a Moving Carrier Problem

Another difficult particle-motion problem on which people demonstrate misconceptions concerns the trajectory of an object dropped from a moving carrier. The error commonly made is to report that such an object falls straight down from the point of release, ignoring the object's horizontal motion component. In their article on people's "straight-down belief," McCloskey and his coauthors proposed a perceptual basis for this misconception: People believe that an object dropped from a moving carrier will fall straight down because they attend to the motion of the object in relation to the carrier (McCloskey, Washburn, & Felch, 1983). McCloskey et al. (1983) then demonstrated that on a variety of problems, people tended to report (either verbally or with drawings) the relative motion of the dropped object when asked to describe its absolute motion.

This tendency to organize the absolute motion of objects into their relative and common components has been long recognized by perceptual psychologists (Duncker, 1929/1938), and it is the basis of several models of perception (e.g., Johansson, 1950). McCloskey et al.'s (1983) contribution was to suggest that this perceptual organization was the basis of people's erroneous motion beliefs.

In the following two experiments, we first attempt to garner support for McCloskey et al.'s (1983) basic conjecture that people form erroneous representations about objects falling from moving carriers in which the object's motion relation to its carrier is represented as its absolute motion. We also demonstrate that when these motions are equivalent (i.e., there is no common motion because the viewpoint moves in a parallel trajectory, or dollies, with the carrier), no such erroneous representations were evoked. In the second study, we examine whether people are able to recognize the canonical outcome within the dynamic context. We predict that such recognition is possible regardless of the organization used for motion representation. The problem we chose for these studies involves an object released from a moving airplane. As shown in Table 2, this problem has been shown to elicit many erroneous responses when administered in a static context (McCloskey, 1983b).

Experiment 2A: Reproducing Viewed Trajectories

This study was designed to verify that viewing an object dropped from an airplane leads to the same sort of motion encoding (i.e., reporting the falling object's motion in relation to the carrier as its absolute motion) that McCloskey et al. (1983) postulated as the basis for the straight-down belief. Thus, in our study, subjects were asked to recreate the trajectory of an object they saw fall from an airplane. This task was very similar to that used in McCloskey et al.'s (1983) Experiment 3, but we used stimuli appropriate for the airplane problem instead of abstract grids and balls. In the McCloskey et al. (1983) task, subjects were asked to view the motion of a ball and a frame on a cathode-ray tube (CRT) and then to draw the path that the ball followed on the screen. In the stimulus events, the ball and grid would initially translate the screen together (i.e., there was common but no relative mo-

Table 2
Percentages of Subjects Producing Forward, Straight Down, or Backward Responses

Study	Forward	Straight down	Backward
McCloskey (1983b)	53	36	11
Experiment 2B dolly condition	82	15	3
Experiment 2B stationary condition	82	18	0

tion), and then a relative motion component was introduced (e.g., the ball would fall as if released from the grid). Subjects' drawings tended to reflect the motion of the ball canonically so long as its motion and the grid's were identical. When a motion that was relative to the grid was introduced, however, the drawings reflected the ball's motion in relation to the grid rather than its absolute motion.

Our task differed from McCloskey et al.'s (1983) in several respects: (a) The events subjects viewed were clearly objects falling instead of abstract motions of balls and grids; (b) the "carrier" in our events (i.e., the airplane) was much smaller than the grid used by McCloskey et al. (1983), and thus it provided a less dominant frame of reference; (c) we used a second set of events in which the vantage point translated parallel to the carrier. (This motion of the vantage point is equivalent to the cinematic technique known as the dolly shot, in which the camera tracks a parallel trajectory to keep the subject in a constant position in the view finder.) Here, because there was no common motion of the carrier and object, the relative and absolute motions of the falling object were equivalent.

Method

Subjects. Forty University of Virginia undergraduates (20 men and 20 women) participated in the experiment for course credit. Although data on physics training were not collected, the sample was drawn from the same population as the previous experiments (although none of the previous participants were included in this sample). It is reasonable to assume that most subjects had taken a physics course in high school, college, or both.

Stimuli and procedure. Animations were generated on an Amiga 1000 microcomputer through the animation package *Videoscape 3D*. The basic event, as depicted in Figure 4, showed an airplane flying over a structured terrain (farm fields in the foreground, mountains in the background). A second airplane was shown on the ground to provide scale and depth information. The flying airplane initially carried a keg of beer under its fuselage that subjects were told was to be air-dropped to the party site in the foreground. After translating the screen at a constant velocity for 1.5 s, the airplane released the keg. Two sets of animations were developed, one with the viewpoint stationary (in which the airplane translated across the screen) and the second with the viewpoint dollying (in which the airplane remained in the center of the screen while the background translated). In the stationary animations, the keg followed one of six trajectories, drawn from the stimuli used in the third experiment of McCloskey et al. (1983). In all alternatives, the keg had a scale-appropriate gravitational acceleration. Compared with the airplane's velocity (assigned a value of 1.0), the keg had the following horizontal velocities.

Trajectory 1: −0.25. This resulted in the keg falling backward from the point of release.

Trajectory 2: 0.00. This resulted in the keg falling straight down from the point of release.

Trajectory 3: 0.50. This resulted in the keg falling with half the forward velocity of the airplane. This is a crude approximation to a canonical outcome given air resistance.

Trajectory 4: 1.00. This resulted in the keg falling with the same forward velocity as the airplane. Given a situation with no air resistance, this is the canonical outcome.

Trajectory 5: 1.00 decreased to 0.50 in the first 0.5 s. This resulted in the keg initially falling with the same forward velocity as the airplane but quickly slowing to half the forward velocity. This is a fair approximation of a canonical outcome given air resistance.

Trajectory 6: 1.20. This resulted in the keg falling with a forward velocity greater than that of the airplane.

These six trajectories corresponded, respectively, to Stimuli 1, 3, 5, 7, 11, and 9 in McCloskey et al.'s (1983) Experiment 3.

Six analogous animations were created for the dolly condition; however, because the airplane's velocity in these animations was 0 (i.e., it remains centered in the screen), 1.0 must be subtracted from the aforementioned values for the keg's forward velocities. The same descriptions of the events apply.

Animations were displayed on a 30–48-cm diagonal color monitor. Subjects were instructed to view each animation twice and then draw the keg's trajectory on a piece of paper with dimensions equivalent to those of the monitor screen. It was stressed that the drawing should be of the keg's trajectory on the screen, such that if the paper were held up to the screen, the keg would follow the path the subject had drawn. Half of the subjects saw the stationary animations first; the others saw the dolly animations first.

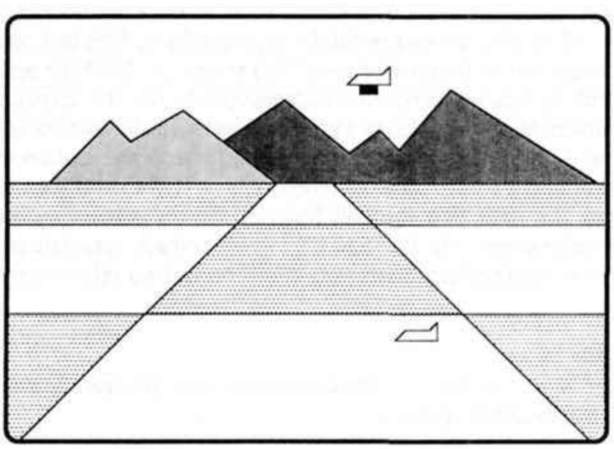

Figure 4. Schematic of the scene used in Experiment 2. (The viewpoint remained fixed for the stationary animations [and the airplane translated]. For the dolly animations, the viewpoint tracked a trajectory parallel to the airplane; this resulted in the airplane maintaining a constant screen position while the background translated.)

Results

Subjects' drawings were classified into one of three categories (backward, straight down, or forward) by three judges, who were paid for their participation. The judges were graduate students, who did not know that the drawings were of falling objects. Interjudge agreement was 94%. Only those drawings judged consistently by all three judges were included for analysis. Figure 5 shows the actual trajectories and the proportion of subjects who produced each kind of drawing after viewing each trajectory for the stationary (left half) and dolly (right half) animations.

As can be seen in the left half of Figure 5, our subjects, like those in the McCloskey et al. (1983) study, tended to underestimate the forward motion of the dropped object in the stationary animations. When the keg's absolute motion was straight down, more than half of the subjects drew trajectories having backward motions. Similarly, when the keg had half of the forward velocity of the airplane, almost half of the

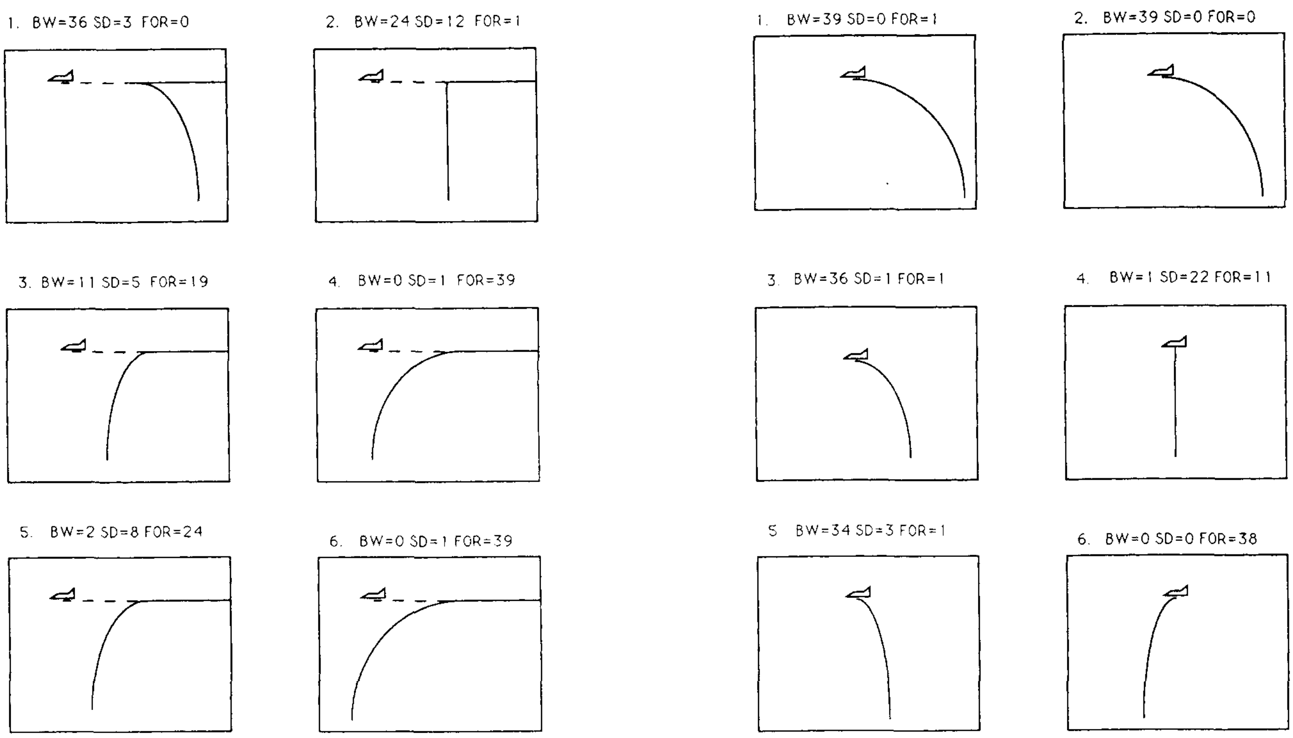

Figure 5. Schematics of the six trajectories for the stationary (left) and dolly (right) animations used in Experiment 2. (The number of subjects in Experiment 2A who produced backward [BW], straight down [SD], and forward [FOR] drawings after viewing each trajectory is listed.)

codable drawings failed to indicate forward motion. Thus, our subjects demonstrated a strong bias to represent the motion of the keg in relation to that of the airplane rather than in terms of its absolute motion.

The relative motion bias demonstrated by our subjects is less pronounced than that noted by McCloskey et al. (1983). After viewing the stimulus in which the object fell with the same forward velocity as the grid, half of their subjects drew trajectories with no forward motion. All but 1 of our subjects indicated forward motion for this case. Most likely, the grid used in McCloskey et al.'s (1983) animations provided a more salient frame of reference than the airplane in our animations. Our airplane was relatively small, whereas their grid extended the entire height of the screen.

The trajectories drawn for the dolly animations, shown in the right half of the Figure 5, showed no systematic bias. Subjects' responses were generally quite accurate, although they had some difficulty reproducing the straight-down trajectory. Here, 6 subjects produced uncodable drawings, and 12 erroneously indicated forward (n = 11) or backward (n = 1) motion. On average, more of the 40 subjects drew correct trajectories for the dolly animations (M = 34.67 subjects) than for the stationary animations (M = 28.17 subjects), $t(5) = 2.70$, $p < .05$.

In general, then, our results replicated McCloskey et al.'s (1983) finding that people's reports of a falling object's absolute motion are influenced by its motion in relation to the carrier that dropped it. This bias is probably more pronounced for more visually dominant carriers. When the dropped object's absolute and relative motions were equated (i.e., the viewpoint dollies with the carrier), people reported the object's motion veridically.

Experiment 2B: Judging the Naturalness of Falling Objects' Trajectories

Experiment 2A demonstrated that our stimuli evoked the same errors in reported trajectories as reported by McCloskey et al. (1983); however, the fact that people organize the dropped object's motion into its components common with and in relation to the carrier (and subsequently report the relative motion as its trajectory) does not imply that they are unable to recognize the natural trajectory when viewing the animated event. We predicted that despite the errors that occur when people represent the falling object's motion for later reports, they nonetheless recognize the canonical trajectory in the dynamical context. This prediction follows from our account that animation fully specifies all necessary motion information for particle systems. Because the motion state of the object is specified, subjects should be able to judge whether the depicted trajectory is natural.

Method

Subjects. Forty University of Virginia undergraduates (20 women and 20 men) participated in this study for course credit. None of these subjects had participated in the previous experiments. All of the men and 12 of the women had taken physics courses in high school, college, or both.

Stimuli and procedure. The stationary and dolly animations from Experiment 2A were used in this experiment. The stimuli were shown on a 47.5-cm diagonal color video monitor to groups of 4 to 5 subjects. Within each of the two animation sets, each trajectory was paired with all other trajectories and shown twice (once ab, once ba). Half of the subjects viewed the stationary animations first, and the other half viewed the dolly set first. Two random orderings of pairs were used. After each pair of trajectories was shown, subjects were asked to indicate which of the two looked more natural or closer to the natural outcome.

Results

We again analyzed subjects' preference judgments in two ways. To compare our data with those of McCloskey, we first determined subjects' most preferred trajectory. Because McCloskey grouped his responses into the three categories of forward, straight down, and backward, we likewise grouped subjects who preferred Trajectories 3–6 into a single category of forward.[5] Note that for both the stationary and dolly animations, the trajectories were grouped by the motion of the keg in relation to the environmental point of release (not, in the dolly animations, to the motion of the keg on the screen). Thus, Trajectories 3–6 were grouped as forward, Trajectory 1 was backward, and Trajectory 2 was straight down for both animation conditions. The proportions of subjects who demonstrated a preference for the forward, straight down, and backward trajectories are shown in Table 2. For both the stationary and dolly animations, 82% of the subjects selected a forward trajectory. This is significantly more than chance (67%) would predict: $\chi^2(1, N = 40) = 8.20$, $p < .005$. Most of the remaining subjects preferred the straight down trajectory (18% in the stationary condition, 15% in the dolly condition). Only 1 subject preferred the backward trajectory in the dolly condition, and none did so for the stationary animations. The distribution of responses was virtually identical for the stationary and dolly animations: $\chi^2(2, N = 40) = 1.08$, *ns*. The proportion of people who preferred forward trajectories in our study is far greater than the proportion who drew forward trajectories in McCloskey's (1983b) study, as shown in Table 2.

Thurstonian Case V scaling solutions of the preference data (see Figure 6) demonstrate that the three canonical alternatives (3–5) are most preferred. The alternatives that model air resistance (3 and 5) are preferred over Alternative 4, which models no air resistance. The scaling solutions are quite similar for the stationary and dolly animations, with similar rankings of alternatives and scale ranges (0.80 and 0.94 nd, respectively).

Discussion

In a previous study, when people were asked to report the trajectory of an object released from an airplane, only about half indicated a forward motion (McCloskey, 1983b). But in Experiment 2B, more than 80% of the subjects preferred the forward trajectories when viewing the ongoing animations.

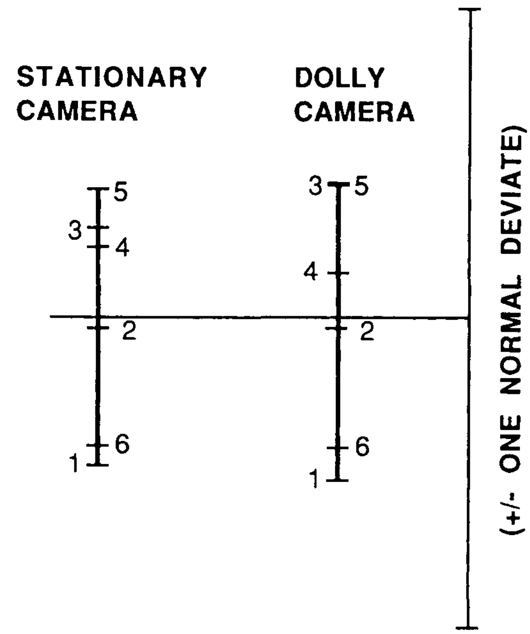

Figure 6. Thurstonian Case V scaling solutions for the preference data from Experiment 2B. (Alternatives 3 and 5 are approximations to a canonical trajectory given air resistance; Alternative 4 is the canonical trajectory given no air resistance.)

As demonstrated in Experiment 2A, the animation stimuli we used evoked the same bias to report the falling object's motion in relation to the carrier as its absolute motion as McCloskey et al. (1983) found with their displays. Yet, given the task of recognizing the canonical outcome, our subjects did just as well under conditions that evoke such biases (i.e., the stationary animations) as in those that did not (i.e., the dolly animations).

Clearly, when asked to judge the naturalness of a trajectory within an animated context, subjects are not required to evaluate the falling object's absolute motion. Animation provides a context in which the motion of the falling object can be evaluated in relation to that of its carrier. So long as this motion is within the range of acceptability, the trajectory is judged as canonical. (For our subjects, this range seemed bounded by the constraint that the object not have a positive velocity in relation to the carrier but could have a somewhat negative value, which reflects the natural occurrence of air resistance.)

Animation increases the veracity of people's dynamical intuitions by providing a context in which their natural per-

[5] Whereas Trajectories 3, 4, and 5 roughly mimic the veridical outcomes with air resistance (Trajectories 3 and 5) and without air resistance (Trajectory 4), Trajectory 6 depicts the keg with a forward velocity greater than that of the airplane. This anomaly was evident to most subjects: only 3 subjects in each animation condition (stationary and dolly) preferred Trajectory 6. Nonetheless, it was included in the forward group for completeness and to allow comparison with the categories of responses (foreword, straight down, and backward) used in previous studies.

ceptual tendencies of motion organization leads to at least qualitatively correct judgments. As was the case for the other particle-motion problems we studied, animation is sufficient to inform observers about the motion parameter of dynamical relevance. What needs to be noticed is the trajectory of the dropped object's center of mass in relation to the plane. Subjects were able to recognize natural trajectories regardless of the motion of biases assessed in drawing contexts.

Notice, however, that animation is not a panacea for dynamical understanding: The representations of motion information are still biased, and reports or dynamical reasoning on the basis of those representations are prone to error. Furthermore, subjects' ability to recognize the natural outcome does not imply that all dynamical judgments (e.g., velocity estimates) are accurate. In fact, people often exhibit biases and insensitivities when asked to make metric judgments concerning object motions. Thus, estimates of velocity can be influenced by perceived distance (Lappin, Bell, Harm, & Kottas, 1975) and object properties (Kaiser, 1990). Furthermore, changes in velocity and other higher order motion derivatives are difficult for subjects to notice (Calderone & Kaiser, 1989). We suggest, however, that observation of animated events is sufficient to inform observers whether they are viewing natural particle dynamics.

Our account suggests that this information is carried in the movement of an object's center of mass over time. For mechanical events that can be adequately characterized as point particle systems, the appropriate representation of this motion provides a sufficient description of the event dynamics. We have shown that this specification of motion state information aids naturalness judgments even for difficult particle-motion problems, that is, those in which there is a transition from extended-body to particle system. Animation has also been shown to affect dynamical judgments on more pure particle-motion problems. Shanon (1976) found that many people gave erroneous descriptions of free fall, reporting either that objects fall at a constant velocity or that the velocity at which they fall is a function of mass. After viewing computer animations of falling objects, however, virtually every subject recognized as natural the constant acceleration of free fall.

We asked subjects to describe the path of a ball dropped from a table's edge or rolled off the edge (Kaiser, Proffitt, & McCloskey, 1985). Unlike Shanon, we only asked subjects to describe the shape of the path, not its velocity function. Given such a task, virtually no adult erred. All correctly stated that the ball released from the edge falls straight down and that the ball rolled off the edge traces a curvilinear trajectory. From a formal analysis, these two problems are equivalent to the apex and nadir pendulum problems, and the rolled-ball problem is equivalent to the beer-keg problem; yet in static contexts, people tend to err on these latter problems. Animation aids people's judgments on these problems by specifying the motion state of the object.

The confusion people demonstrate on the pendulum problems also stems from juxtaposition of the bob's dimensional state in extended-body and particle systems. Animation resolves this confusion by providing a temporal segregation of the two motion contexts. This temporal segregation can also aid dynamical judgments for some special cases of extended-body systems. These are cases in which a single dimension of the motion system is adequate for dynamic specification. That is, there exist one-dimensional slices of the multidimensional problem; within these planes of the problem space, a single parameter is dynamically informative. In such cases, animation can evoke accurate judgments of naturalness.

Experiment 3: The Liquid-Displacement Problem

A set of studies we have performed on people's understanding of water displacement demonstrates how it is possible for animation to aid dynamical understanding in multidimensional domains. Within the framework we have proposed, floating bodies are examples of extended-body systems: No single parameter specifies the volume of water an object will displace. As discovered by Archimedes, the density of an object classifies it into either objects that sink or objects that float. Different object descriptors define the volume of water such objects will displace: Sunken objects displace a quantity of water equal to their volume, and floating objects displace a quantity of water equal to their mass.

It is possible to construct problem categories that are one-dimensional slices of this problem space. Within a category, only one object descriptor has dynamical relevance. People should be able to deal with such problems so long as they fall within these categories. Thus, given two floating objects (i.e., density less than water), people should be able to predict that the heavier one will displace more water. Similarly, people should correctly predict that the larger of two sunken objects displaces more water. What should exceed their competence is a problem that crosses these categories and requires the integration of multiple informational dimensions. Hence, a problem that requires the comparison of sunken and floating objects is extremely difficult. Consider the following problem:

> I have a toy boat floating in a small tub of water. Into this boat I place a heavy metal bolt. I mark the water level on the side of the tub. Now I take the bolt out of the boat and place it in the tub of water. The bolt sinks to the bottom of the tub. I again mark the water level on the tub's side. Will the two marked water levels be the same? If not, which one will be higher?[6]

The correct answer is that the water level will be lower with the bolt sunken in the water. Arriving at this answer, however, requires one to shift attention from the mass of the bolt when it is in the boat to the volume of the bolt when it is in the water.

In the following experiments, we investigated people's ability to reason about simple and complex displacement problems. A simple problem represents a one-dimensional slice of the problem space. Displacement can be judged either solely on the basis of mass (when both objects float) or volume (when both objects sink). Complex problems require that comparisons be made across informational dimensions, as in

[6] This problem is adapted from Walker (1975), which includes the interesting anecdote that three renowned physicists, Robert Oppenheimer, Felix Block, and George Gamow, were unable to give a correct answer to the problem.

the bolt-in-the-boat problem. The first experiment examined people's competence on these simple and complex problems in a static context. We predicted that people should perform well on the simple problems but fail on the complex problems. We also predicted that if extraneous parameters are varied on simple problems (e.g., shape or mass distribution), people will make errors. These errors, like those found for the pendulum and C-shaped-tube problems, result from people overestimating dynamical complexity when evaluating the system in a static context.

We then performed a second study to examine whether animation can aid people's naturalness judgments on a complex displacement problem, the bolt-in-the-boat problem. Our framework predicts that animation can aid judgments by temporally parsing the complex problem into two temporal intervals: the epoch in which mass is the relevant parameter (when the bolt is in the floating boat) and that in which volume is relevant (when the bolt is sunken in the water). Because each of these epochs requires attention to only a single parameter of dynamical relevance, subjects should be able to discriminate natural and unnatural displacement outcomes within each epoch.

Experiment 3A: Static Displacement Problems

People were administered a series of questions about the relevant displacement of two objects. We varied whether problems could be solved by attending to a single parameter or required attention to more than one informational dimension. We also created problems whose solutions required only a single parameter but whose surface structure resembled multidimensional problems because of the concurrent variation of an irrelevant parameter.

Method

Subjects. Forty-eight University of Virginia undergraduates (24 men and 24 women) participated in this study for course credit. None had participated in the previous experiments. Of the men, all but 2 had taken a physics course in high school, college, or both. Five of the women had never taken a physics course.

Materials and procedure. Subjects were administered an interview consisting of 32 randomly ordered questions about fluids, with accompanying diagrams. Each subject received a different order of questions. Sixteen of these questions were filler questions dealing with fluid properties unrelated to displacement. Two of the questions dealt with the displacement properties of sponges and are not of current interest. Of the remaining 14 questions, 6 were simple problems, varying only a single dimension of the objects and comparing objects that were either both floating or both sunken (3 cases of each). The single dimension varied could be mass (relevant only for floating objects), volume (relevant only for sunken objects), or shape (not relevant for either floating or sunken objects).

The next four questions we termed pseudocomplex. Here, answers could still be based on a single dimension, mass, because both objects were floating. An irrelevant parameter was varied in these problems, however, adding a false sense of complexity. In three of the four problems, the objects were composed of two components, one of which is denser than water, the other less dense. Subjects needed to compare the case in which the less dense portion was submerged with that in which the more dense portion was submerged (see Figure A1). In the fourth pseudocomplex question, a material with a density greater than water was shaped into two floating containers of differing volumes (see Panel 3 of Figure A1). Neither the mass distribution nor the volume of the floating objects mattered, but the inclusion of these parameters may have led subjects to believe that they were of dynamical relevance.

The final set of four questions, which we termed complex, involved true extended-body systems. In these, there was a transformation, either across time or between objects, which required that one attend to information across dimensions; that is, the mass of an object in one case must be compared with its volume in the other. The bolt in the boat was one such problem. The other complex problems, together with the simple and pseudocomplex problems used in this study, appear in the Appendix.

The experimenter read each question to subjects as they viewed an accompanying diagram. Subjects responded on an answer sheet whether the two objects would displace identical or different amounts of water; if *different* was the response, subjects indicated which object displaced more.

Results

As predicted, subjects performed well when the displacement problems were constrained to vary along a single dimension. Subjects gave correct responses to these simple problems 78% of the time. Varying a second, irrelevant parameter on these problems muddled subjects' reasoning: Performance on the pseudocomplex problems was only 47% correct. Finally, subjects performed poorest on the true extended-body-system questions. Only 20% of the answers to the complex questions were correct.

The proportion of correct responses differed significantly among the three categories of problems: $\chi^2(2, N = 48) = 30.40$, $p < .001$. Performance on the simple problems was significantly better than chance (33%): $\chi^2(1, N = 48) = 41.34$, $p < .001$. On the pseudocomplex and complex problems, performance did not differ significantly from chance: $\chi^2(1, N = 48) = 4.59$ and 3.37, respectively. The proportion of correct responses was not affected by the level of subjects' physics training; however, there was a significant gender effect across problem type, $\chi^2(1, N = 48) = 7.59$, $p < .01$, with males producing a greater proportion of correct responses.

Even in a static context, people were able to predict the outcome of simple displacement problems so long as an accurate judgment could be based on a single parameter of dynamical significance. They did not, however, seem able to construe well a dynamically relevant change in the dimensional state of an object. Furthermore, their ability to recognize the parameter of dynamical significance was inhibited by the inclusion of extraneous variables. By varying irrelevant dimensions in the pseudocomplex problems, we reduced subjects' recognition of the simple displacement problem. In much the same way, the C-shaped-tube and pendulum problems reduce people's ability to recognize the simple particle motion by including a prior extended-body context that is extraneous to the object's current motion state.

Experiment 3B: Judging the Naturalness of Displacement Events

We have demonstrated that people are able to reason correctly about displacement only in the context of simple, unidimensional problems. When multiple dimensions are varied, subjects become confused about the proper influence of these parameters, even if one of the parameters is irrelevant to the problem. Performance is worst on those problems that genuinely require subjects to construe different dimensions of information (i.e., mass and volume). In this experiment, we examined whether people perform better on one of these complex problems in an animated context.

For this study, we selected the bolt-in-the-boat problem. This problem was selected because it should benefit from the temporal parsing provided by animation. While the bolt is in the floating boat, its displacement is determined by its weight. When sunk in the water, the bolt will displace its volume. Animation should allow people to judge the naturalness of the bolt's displacement in each of these epochs because it segregates the bolt's two dimensional states: When in the boat it is a heavy object, and when sunk it is a small object.

On the static task, only 21% of the subjects correctly responded that the bolt displaces more water in the toy boat (where it displaces an equivalent mass of water) than when sunk in the tub (where it displaces only its volume). Thirty-nine percent of the subjects thought the water level would be the same in both cases, and 40% thought it would be higher with the bolt in the water. Would subjects who view this transformation perceive these erroneous outcomes as natural?

On the basis of our account, we predicted that subjects will reject these anomalous outcomes and recognize the natural displacement event because the perceptual context separates the relevant variables in time. When the heavy metal bolt is placed in the boat, subjects can see that it pushes the boat into the water with its weight. When the bolt is removed from the boat and placed in the water, subjects can see that it is no longer part of the boat, but rather a sunken object whose volume determines displacement. The event dynamics provide a temporal parsing: The bolt is part of a floating system in the first epoch, and it is a sunken object in the second. Within each epoch, perception informs us whether the amount of water displaced appears veridical.

Method

Subjects. Six male and 6 female University of Virginia undergraduates were paid to participate in this study. None was involved in the previous experiments. All but 1 of the men and 1 of the women had taken a physics course in high school, college, or both.

Materials and stimuli. A water tank was constructed such that water could be added or removed without noticeable turbulence to the system. This allowed us to make videotapes of displacement events in which the resulting changes in the water level could be natural or anomalous. For natural events, no water was added or removed from the main tank. To create anomalous events, a piston

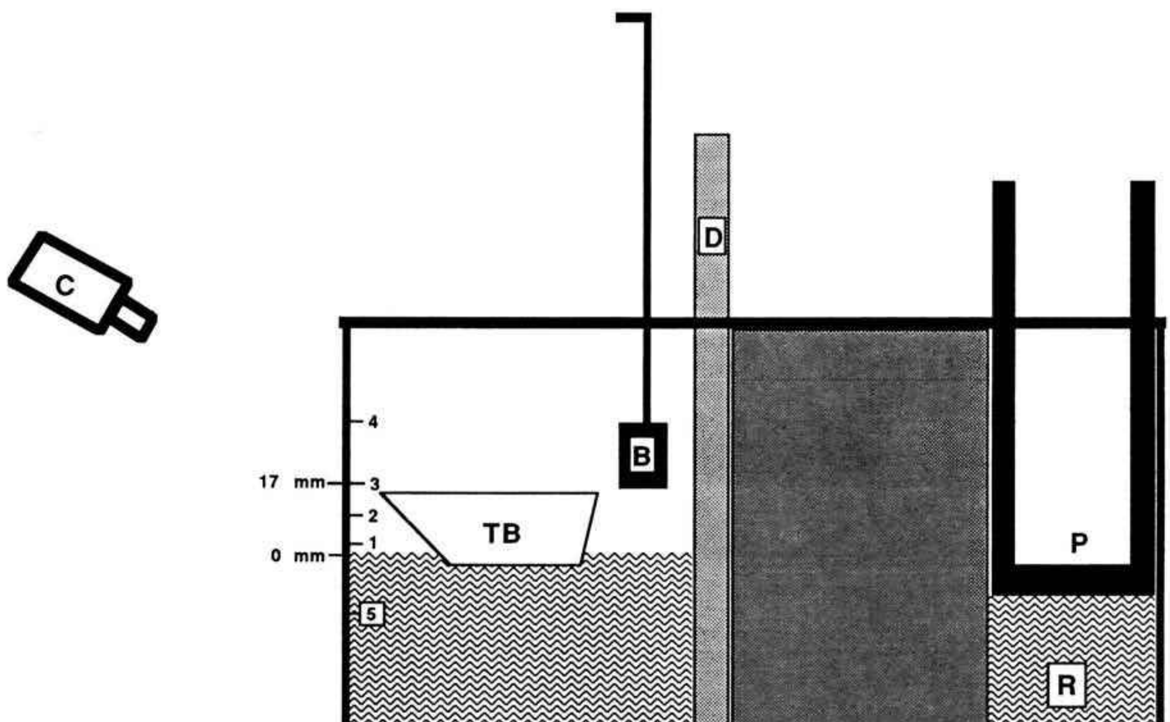

Figure 7. Schematic of the experimental apparatus used to create videotaped stimuli for Experiment 3B. (The change in water level that occurs when the bolt [B] is placed in the water can be manipulated by raising or lowering a piston [P] and transferring water to or from a reserve tank [R]. The camera [C] is positioned so that these mechanisms involved in artificially altering the displacement events are hidden from view by the divider [D], which separates the reserve tank from the main tank where the toy boat [TB] floats. The water levels for the bolt in the boat [17 mm], for the boat with the bolt removed [0 mm], and for the five displacement stimuli [1–5] are indicated.)

could be raised or lowered to transfer water to or from a hidden reserve tank. A schematic (not to scale) of the experimental apparatus is shown in Figure 7. The relative sizes of the toy boat, bolt, and water tank used in this experiment were similar to those depicted in the diagram accompanying the static context problem in Experiment 3A.

Videotapes of five displacement events were made. All events began with the same sequence in which the toy boat (actually a bread pan) was shown floating in the water. A heavy metal cylinder was placed in the boat, causing the water level to rise 17 mm. This bolt was then removed from the boat, and the water level dropped to its original level. Up to this point, all five events were identical and natural. The events then continued with the bolt being placed in the water, resulting in one of five alternative outcomes.

Alternative 1. The water rose naturally (2 mm).

Alternative 2. The water rose more than a veridical amount but to a level lower than with the bolt in the boat (9.5 mm).

Alternative 3. The water rose to the same level as when the bolt was in the boat (17 mm).

Alternative 4. The water rose to a level higher than when the bolt was in the boat (32 mm).

Alternative 5. The water fell (−15 mm).

Note that Alternative 4 depicted an event in which the water level is higher with the bolt in the water (the most common erroneous response in the static condition), and Alternative 3 depicted an event in which the water level is the same for the bolt in the boat and the water (another common error made on the static problem), whereas Alternatives 1 and 2 depicted events in which the water level was lower with the bolt in the water (a response given only 21% of the time on the static problem). Alternative 1 was a natural displacement event, and Alternative 2 was qualitatively correct (i.e., the water rose when the bolt entered the water but not as much as when it was placed in the boat). Alternative 5 was truly anomalous: The bolt had a negative displacement as it entered the water. The master videotape of the five events was edited such that each event (starting with the empty boat floating in the water and ending with the bolt submerged in the tank) was paired with all other events twice (e.g., once ab, once ba). This created 20 test trials.

Procedure. Subjects were tested individually. The experimenter showed the subject the actual water tank, bolt, and boat that were used (to ensure that subjects had a proper sense of the objects' sizes) and demonstrated how the water level could be manipulated with the piston and hidden reserve tank. The experimenter then explained that they would view videotaped pairs of events created with this apparatus and judge the extent to which the experimenter artificially altered the outcome of the event by moving the piston. The subject was then shown 5 practice trials without feedback (chosen from the 20 test trials) followed by the 20 test trials. For each trial, the subject was asked to select which event of the pair appeared less artificial (i.e., involved the least amount of experimenter manipulation). Two orders of trial presentation were used.

Results

Again, we analyzed the preference data in two ways. First, to compare performance with that in Experiment 1A, we determined subjects' most preferred alternative (1 subject's responses were inconsistent, and no such determination could be made). Both Alternatives 1 and 2 can be equated with a correct response on the static problem (i.e., the water level is lower with the bolt in the water than with the bolt in the boat) and were the most preferred alternatives for 10 of the 12 subjects. This should be compared with only 21% who gave correct responses to the problem in Experiment 3A. Only 1 subject preferred Alternative 3, in which the water level was the same (compared with 39% in Experiment 3A); furthermore, no subject preferred Alternative 4, in which the water level was higher (compared with 40% in Experiment 3A). In the dynamic context, this higher water-level outcome was perceived as absurd. Alternative 5, in which the water level actually falls when the bolt enters the tank, was likewise dismissed by subjects. The distribution of responses in the representational context of Experiment 3A differed significantly from that in the dynamic context of Experiment 3B: $\chi^2(2, N = 60) = 19.87$, $p < .001$. There were no effects for gender or level of physics education on performance in the dynamic context.

Thurstonian Case V scaling of the preference data (Figure 8) confirmed that Alternatives 1 and 2 are most preferred. Alternative 4, which corresponds to the most common response on the static version of the problem, had a negative scale value. The range of the scale was 2.25 nd, indicating good discriminability among the alternatives.

Discussion

Like the previous experiments that studied how animation affects dynamical judgments on the C-shaped-tube, pendulum, and falling-object problems, the current experiments on

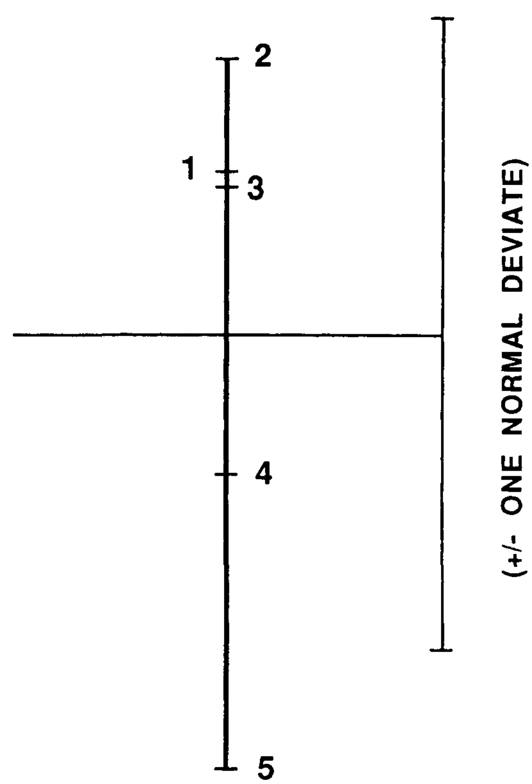

Figure 8. Thurstonian Case V scaling solution for the preference data from Experiment 3B. (Alternatives 1 and 2 are qualitatively canonical outcomes. Alternative 4 corresponds to the most common response given to this problem in Experiment 3A.)

displacement problems demonstrate that people give far more accurate responses in a dynamic context, viewing ongoing events. On the C-shaped-tube, pendulum, and falling-object problems, animation specifies the motion state of the object's center of mass. This information is sufficient to judge the naturalness of these particle systems. Animation serves a second function on the C-shaped-tube and pendulum problems; it provides a temporal parsing of dimensional states. That is, it separates the initial interval in which the ball or bob is part of an extended-body system from the epoch in which the object can be viewed as a particle point. Although displacements are inherently extended-body problems, there are slices of the problem space (i.e., when all objects under consideration are floating or sunken) that can be solved by attending to a single object dimension. For floating objects, this is the objects' mass; for sunken objects, it is their volume. In the ongoing event shown in Experiment 3B, subjects could base their judgments on whether the amount of water displaced when the bolt was lowered into the water appeared appropriate for the volume of the bolt. Thus, animation informs subjects about the naturalness of these one-dimensional slices of an extended-body system.

General Discussion

Animation serves two functions that can aid people's dynamical judgments. First, it allows people to observe directly an object's center-of-mass kinematics. For an event properly characterized as a particle-motion system, this is a fully adequate description of the system's dynamically relevant motion state. Thus, we expect people to make accurate naturalness judgments when viewing such systems. Our studies on particle-motion problems indicate that this is the case.

Second, animation segregates in time changes in the dimensionality of an object's motion. As suggested in an earlier article on understanding natural dynamics (Proffitt & Gilden, 1989), people do well only on problems that can be adequately characterized by a single dimension of dynamical relevance. Thus, they err on higher dimensional problems or problems that are misconstrued as being multidimensional. This misconstruction of unidimensional problems explains the errors commonly observed on the C-shaped-tube and pendulum problems as well as the errors we observed on the pseudocomplex displacement problems in Experiment 3A. In all of these cases, errors resulted when the complexity of a motion system was overestimated. In the C-shaped-tube and pendulum problems, people's errors reflected a belief that the point particle's motion is somehow still influenced by the extended-body system of which it is no longer a part. Similarly, subjects' reasoning on the pseudocomplex displacement problems became muddled by the inclusion of a dynamically irrelevant variable; subjects then failed to demonstrate the competence shown on the formally equivalent simple problems.

This same confusion occurred on the C-shaped-tube and pendulum problems. No adult incorrectly predicted the trajectories of objects released from the edge or rolled off of a cliff (Kaiser, Proffitt, & McCloskey, 1985). These situations are formally equivalent to the apex and nadir pendulum problems, respectively. But on the pendulum problems, confusion arises from the proximity of the extended-body-system context. Animation separates the extended-body and point particle contexts for the C-shaped-tube and pendulum problems. Similarly, animation temporally parses the bolt-in-the-boat problem into two unidimensional problems: the displacement of the bolt's weight when in the boat and the displacement of its volume when sunk.

The Limits of Information Animation Provides

As we have discussed, animation does not evoke dynamical appreciations of extended-body systems (Proffitt et al., 1990). Our perceptual system does not spontaneously form multidimensional dynamical quantities. Thus, systems whose dynamics are determined by such higher order parameters are perceptually impenetrable: Their workings appear arbitrary or magical.

There are situations, however, in which people are facile in understanding extended-body systems. These involve one-dimensional slices through the problem space. Within these slices, the behavior of a system can be predicted on the basis of a single, perceptually salient parameter. One example of such parameterization was discussed in the experiments on people's understanding of Archimedes' principles. Within the problem set, which varied a single dimension of dynamical relevance, people demonstrated competence. Similarly, animation served to temporally parse the bolt-in-the-boat problem into two epochs, each of which could be evaluated in terms of a single displacement parameter.

Another example of this unidimensional parameterization has been delineated for collision events (Gilden & Proffitt, 1989). Here, the competencies that have been demonstrated for making dynamical evaluations of these extended-body events (Kaiser & Proffitt, 1987; Todd & Warren, 1982) were shown to result from a number of unidimensional heuristics, each of which provides correct information within a constrained subset of the problem space. Animation can thus be helpful for extended-body systems when it focuses attention on a particular parameter of the system that has heuristical utility. In other situations, however, animation can be ineffectual.

We now return to the example of the gyroscope. As we have discussed, the gyroscope is a classic example of an extended-body system: It is often used as a teaching example of such systems in physics curricula. Watching a gyroscope as it spins and precesses is magical; it continues to stay upright when any "proper" object would fall over.

This apparent failure of the gyroscope to behave as we expect an object to behave illustrates how animation can fail to inform us. We think the gyroscope should fall over because its center of mass (which corresponds to the centroid of the form for an object of uniform density) is not balanced over its support. We erroneously apply a point particle analysis to this extended-body system. A nonspinning gyroscope in a tilted orientation *would* tumble over; our perceptual analysis of the spinning gyroscope informs us that it should do the same. When it does not, children of all ages (including professional physicists) are charmed.

Another limitation of the role animation can play in aiding dynamical intuitions is the failure of insights lent by animation to generalize to static, representational contexts. It does not seem that people spontaneously reorganize their motion concepts on the basis of their perceptual appreciations of the dynamical systems. Thus, we see the recurrent lack of order effects in our animated versus static context tasks; having just successfully recognized a canonical event in a dynamic context does not aid one's ability to reason about such problems or even recognize a static representation of the solution. The insight gained through animation is difficult to recapture through imagery or symbology. It is perhaps as elusive as the recovery of motion-specified shape (Wallach & O'Connell, 1953) or depth order (Gibson, Gibson, Smith, & Flock, 1959) once the motion has ceased.

Given that our perceptual appreciations do not spontaneously form the basis of our conceptual understanding of dynamics, how do we reason about mechanical problems?

Models of Intuitive Mechanics

For McCloskey and other researchers studying the intuitive understanding of mechanics, subjects' errors are seen not as random but rather as reflecting mental models at variance with the Newtonian framework. A further "ontogeny recapitulates phylogeny" argument is often advanced which compares subjects' intuitive models with historical predecessors of the Newtonian model. The two historical models most often cited are the theory of Aristotle and the medieval impetus theory. Both are internally consistent models of object motion whose assumptions differ significantly from those of Newtonian mechanics.

The Aristotelian Model

As put forth in his *Physics*, Aristotle (Hope, 1961) proposed that objects move for two reasons: first, to seek their natural place (e.g., "fire upward, and earth downward and towards the middle of the universe," p. 73). This is called *natural motion*. Second, objects can undergo violent motion as the result of a force acting on them. This requires that the object remain in contact with the mover or be connected through a transmitting medium: "The air which has been pushed pushes projectiles with a motion more vigorous than their motion to their resident place. But none of these things can happen in a void: there, a body can continue moving only as long as it is propelled by something else" (p. 74).

Several researchers claim to have found evidence of Aristotelian thinking among their subjects. Shanon's (1976) examination of college students' beliefs about falling objects noted that a substantial proportion of the students gave responses that could be regarded as Aristotelian. These were responses that held either that objects fall at a constant velocity or that the rate at which an object falls is proportional to its mass. In his earlier writings, diSessa (1982) likewise argued that the strategies used by both elementary school children and college students in playing a computer game demonstrated Aristotelian tendencies. The game required that a cursor be moved to a target by applying "kicks," or impulses, to the cursor. DiSessa found that many of his subjects persisted in strategies that assumed that the cursor would move in the direction of the last kick instead of in the direction of the vector sum of the forces applied. (In subsequent research, diSessa noted a lack of consistency in subjects' reasoning and has become disenchanted with any sort of "theory theory" concerning naive physical reasoning, diSessa, 1983.)

The Impetus Model

McCloskey (1983) argued that people's intuitive model of motion is neither Aristotelian nor Newtonian but rather resembles a medieval correction to Aristotle's account of motion, termed the *theory of impetus*. Clearly, the Aristotelian model had difficulties with projectile motion, and the theory of impetus sought to circumvent this by proposing that the mover imparts to an object an internal energy, or impetus. This impetus then maintains the object's motion until it dissipates either spontaneously or because of external influences such as air resistance. McCloskey claims to have found evidence of impetus-type thinking on a variety of problems. Some sample beliefs are (a) that projectiles exiting a curved tube will continue to curve because the object has acquired a curvilinear impetus and (b) that an object dropped from a moving carrier will fall straight down because the forward impetus "belongs" to the carrier.

In Search of Intuitive Pre-Newtonians

An obvious challenge to those who would characterize errors on motion problems as reflective of pre-Newtonian motion models is to demonstrate the sort of internal consistencies such models would predict. Does a particular subset of subjects give consistent Aristotelian or impetus responses to a variety of motion problems? Interestingly, this question is usually not systematically examined by those who advance such historical models; their results report the proportions of Aristotelian or impetus responses independently for each problem, with no indication of correlation of response type across problems. In his study, Shanon noted that responses were not consistent across question format or type (i.e., acceleration vs. mass) and concluded that people do not have a consistent model of motion. Our own data and those of Ranney and Thagard (1988) suggest that the same person will give responses that reflect several motion models; furthermore, we have shown that merely varying surface structure of a motion problem can greatly effect the sophistication of a person's response (Kaiser, Jonides, & Alexander, 1986). In short, there is little evidence to suggest that people base their reasoning on any sort of consistent internal model of motion, be it Aristotelian, impetus, or Newtonian.

We have proposed an alternative model of common-sense dynamical understanding (Proffitt & Gilden, 1989). Our model proposes that people base their common-sense dynamical judgments on one informational dimension within an event. People do not make dynamical judgments by deriving multidimensional quantities. It then follows that people generally make accurate dynamical judgments in one-dimensional (e.g., particle-motion) contexts and those multidimensional (e.g., extended-body) contexts that are constrained such that specific judgments can be accurately derived from a single informational dimension. People perform poorly in multidimensional contexts or in particle-motion contexts that are misconstrued as multidimensional. We concluded that many of the errors reported in the intuitive physics literature are elicited by particle problems that are misconstrued as multidimensional. These problems often involve a transition from an extended-body to a particle-motion context.

The inclusion of the extended-body context confuses people when they are asked to reason about these problems. No adult errs when asked to describe the path of a ball dropped from the edge or rolled off a table, yet errors are made on the formally equivalent pendulum problems because of the inclusion of the extended-body context. Similarly, even preschoolers know that a ball given a push will roll straight (Kaiser, Proffitt, & McCloskey, 1985). Again, the formally equivalent problem placed in proximity to an extended-body context (i.e., the C-shaped tube) evokes errors.

Animation aids dynamical judgments on these problems by temporally parsing the particle-motion and extended-body contexts. Once the observer views the object within the appropriate unidimensional context, the necessary information about the motion state of the system is fully specified by the object's center of mass kinematics. Furthermore, this specification of motion state is sufficient for accurate naturalness judgments regardless of whether an object-centered or environment-centered frame of reference is adopted.

Conclusions

Thus, our account specifies in what cases animation will aid people's dynamical judgments. There are three principal conclusions to be drawn.

Animation will provide a basis of perceptual penetration only for those dynamical systems that can be properly characterized by a single parameter of dynamical significance. This constraint is met by point particle systems as well as by one-dimensional slices of extended-body systems' parameter space. If animation is to enhance competence with extended-body systems, it must be structured to focus people's attention on a dimension of heuristical utility.

The dynamical insights gleaned from animation do not necessarily generalize to static, representational contexts. There is no automatic mapping from the kinematics to any symbology. Some physics curricula have incorporated animations as teaching devices. The best of these (e.g., Blinn, 1989) recognize the need to link explicitly the symbology to the underlying kinematics. Even with such linkages, it may be difficult for people to transfer their perceptual appreciations into formal, representational understandings; without them, there is virtually no evidence for such transfer.

Despite these limitations, the animated instantiation of a dynamical system provides a context in which people can demonstrate a level of dynamical competence that far exceeds their common-sense reasoning regarding such systems. People's perception-based competence can be exploited by those who design displays for science education and for the control and monitoring of dynamical systems.

In fact, it is people's competence with the dynamics of such ongoing events that led many of us to greet the early findings in the intuitive physics literature with the incredulous question, "Can you believe that people actually think a ball continues to curve when it exits a C-shaped tube?" We somehow thought that people were smarter than that. In a significant class of dynamic contexts, they are.

References

Aristotle. (1961). Natural science and its principles. In R. Hope (Trans.), *Physics* (pp. 68–82). Lincoln: University of Nebraska Press.

Blinn, J. (1989). The making of "The Mechanical Universe." In S. R. Ellis, M. K. Kaiser, & A. J. Grunwald (Eds.), *Spatial displays and spatial instruments* (NASA Conference Publication 10032, pp. 45-1–45-18). Moffett Field, CA: NASA Ames Research Center.

Calderone, J. B., & Kaiser, M. K. (1989). Visual acceleration detection: Effect of sign and motion orientation. *Perception & Psychophysics, 45,* 391–394.

Caramazza, A., McCloskey, M., & Green, B. (1981). Naive beliefs in "sophisticated" subjects: Misconceptions about trajectories of objects. *Cognition, 9,* 117–123.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121–152.

Coombs, C. H. (1964). *A theory of data.* New York: Wiley.

diSessa, A. (1982). Unlearning Aristotelian physics: A study of knowledge-based learning. *Cognitive Science, 6,* 37–75.

diSessa, A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 15–33). Hillsdale, NJ: Erlbaum.

Duncker, K. (1938). Induced motion. In W. D. Ellis (Ed.), *A sourcebook of Gestalt psychology* (pp. 161–172), London: Routledge & Kegan Paul. (Original work published 1929)

Flavell, J. H. (1977). *Cognitive development.* Englewood Cliffs, NJ: Prentice-Hall.

Genter, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 99–129). Hillsdale, NJ: Erlbaum.

Gilden, D. L., & Proffitt, D. R. (1989). Understanding collision dynamics. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 372–383.

Gibson, E. J., Gibson, J. J., Smith, O. W., & Flock, H. R. (1959). Motion parallax as a determinant of perceived depth. *Journal of Experimental Psychology, 58,* 40–51.

Howard, I. (1978). Recognition and knowledge of the water-level problem. *Perception, 7,* 151–160.

Johansson, G. (1950). *Configurations in event perception.* Uppsala, Sweden: Almqvist & Wiksell.

Kaiser, M. K. (1990). Angular velocity discrimination. *Perception & Psychophysics, 47,* 149–156.

Kaiser, M. K., Jonides, J., & Alexander, J. (1986). Intuitive reasoning about abstract and familiar physics problems. *Memory & Cognition, 14,* 308–312.

Kaiser, M. K., & Proffitt, D. R. (1987). Observers' sensitivity to dynamic anomalies in collisions. *Perception & Psychophysics, 42,* 275–280.

Kaiser, M. K., Proffitt, D. R., & Anderson, K. A. (1985). Judgments of natural and anomalous trajectories in the presence and absence of motion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 795–803.

Kaiser, M. K., Proffitt, D. R., & McCloskey, M. (1985). The development of beliefs about falling objects. *Perception & Psychophysics, 38,* 533–539.

Lappin, J. S., Bell, H. H., Harm, O. J., & Kottas, B. (1975). On the relation between time and space in the visual discrimination of velocity. *Journal of Experimental Psychology: Human Perception and Performance, 1,* 383–394.

McAfee, E. A., & Proffitt, D. R. (1991). Understanding the surface orientation of liquids. *Cognitive Psychology, 23,* 483–514.

McCloskey, M. (1983a). Intuitive physics. *Scientific American, 248,* 122–130.

McCloskey, M. (1983b). Naive theories of motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 299–324). Hillsdale, NJ: Erlbaum.

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

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

Proffitt, D. R., & Cutting, J. E. (1980). An invariant for wheel-generated motions and the logic of its determination. *Perception, 9,* 435–449.

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

Proffitt, D. R., Kaiser, M. K., & Whelan, S. M. (1990). Understanding wheel dynamics. *Cognitive Psychology, 22,* 342–373.

Ranney, M., & Thagard, P. (1988). Explanatory coherence and belief revision in naive physics. In Hillsdale, NJ: Erlbaum. *Proceedings of the Tenth Annual Conference of the Cognitive Science Society* (pp. 111–117).

Runeson, S. (1977). *On visual perception of dynamic events.* Unpublished doctoral dissertation, University of Uppsala, Uppsala, Sweden.

Shanon, B. (1976). Aristotelianism, Newtonianism, and the physics of the layman. *Perception, 5,* 241–243.

Simon, D. P., & Simon, H. A. (1978). Individual differences in solving physics problems. In R. S. Siegler (Ed.), *Children's thinking: What develops?* (pp. 325–348). Hillsdale, NJ: Erlbaum.

Todd, J. T., & Warren, W. H. (1982). Visual perception of relative mass in dynamic events. *Perception, 11,* 325–335.

Torgerson, W. S. (1958). *Theory and methods of scaling.* New York: Wiley.

Walker, J. (1975). *The flying circus of physics.* New York: Wiley.

Wallach, H., & O'Connell, D. N. (1953). The kinetic depth effect. *Journal of Experimental Psychology, 45,* 205–217.

Appendix
Simple, Pseudocomplex, and Complex Displacement Problems From Experiment 3A

Simple

Problem 1. Imagine that you have two cubes identical in size. One is made of wood and the other of styrofoam. Both are painted with blue waterproof paint. The wooden cube is heavier. You also have two small buckets that are the same size and shape. You have filled each bucket with a quart of water so that the water levels are identical in each bucket. You now place the wooden cube in one bucket and the styrofoam cube in the other. They both float. Will the water levels of the two buckets remain equal? If not, which one would be higher? (Answer: The bucket with the wood cube will have a higher water level.)

Problem 2. I have a cork block and a wooden block. The cork block is sufficiently larger than the wooden block so that they weigh the same amount. Both objects float if placed in water. I also have two beakers of water like the ones in the diagram. I notice that the water levels of the two beakers are equal. If I were to place the wooden block in one beaker and the cork block in the other, would the water levels of the beakers remain equal? If not, which one would be higher? (Answer: The water levels remain equal.)

Problem 3. Imagine that you have two pieces of styrofoam that are identical in size and weight. You shape one piece into a cube and the other into a bar. You are given two glasses. You fill each glass with 2 cups of water so that their water levels are equal. Next you place the cube in one of the glasses and the bar in the other to see if they float. They both do. Will the water levels in the two glasses remain equal after you place the objects in them? If not, which one will become higher? (Answer: The water levels remain equal.)

Problem 4. I have a piece of aluminum and an equal volume of lead. I decide to make a lead bullet and an aluminum bullet out of each of these. The bullets are the same size and shape, but the aluminum bullet is much lighter. I want to see if they will float in water, so I obtain two identical glasses. I fill each glass with 3 cups of water so that the water levels of the glasses are equal. I put one bullet in each glass and see that they both sink. Will the water level of the two glasses remain equal? If not, which one will now be higher? (Answer: The water levels remain equal.)

Problem 5. Mrs. Jones and Mrs. Smith each found a bead. Mrs. Jones's bead is made out of aluminum, and Mrs. Smith's is made out of lead. Both beads weigh the same amount, which means that the aluminum bead must be sufficiently larger than the lead one. Both Mrs. Jones and Mrs. Smith wish to wash their beads. They each obtain buckets that happen to be identical in size and shape. Both fill their buckets with a pint of water so that the water levels are equal. They now place their beads in the water and watch them sink to the bottom of the buckets. Have the water levels of the two buckets remained equal? If not, which one is now higher? (Answer: The bucket with the aluminum bead will have a higher water level.)

Problem 6. I have two pieces of iron that are identical in size and weight. I decide to make a ball out of one and a bar out of the other. I also have two pans that are the same size and shape. The pans are each filled with the same amount of water so that the levels of water are equal. I now place the ball in one pan and the bar in the other. Both sink to the bottoms of the pans. Have the water levels remained equal? If not, which one will now be higher? (Answer: The water levels remain equal.)

Pseudocomplex

Problem 1. I have two clay balls that are identical in size, shape, and weight. I also have two pieces of styrofoam shaped like bars. To make the clay balls float, I attach one of the styrofoam bars to the top of one of the clay balls with a strong adhesive. I then place the other styrofoam bar on the bottom of the other clay ball. To test whether they float, I obtain two beakers that are the same size and shape. I fill each beaker with a quart of water so that their water levels are equal. I then place one of the clay-foam objects in each of the beakers. I find that they both float. Will the water levels still be equal? If not, which will now be higher? (Answer: The water levels will still be equal; see Panel 1 of Figure A1.)

Problem 2. You are given two styrofoam bars that are the same weight and size. You are also given two pieces of clay that are identical in size and weight. You shape the first piece of clay into a rod and roll the second into a ball. You are then given two identical jugs with equal water levels. You are told to put one of the pieces of clay into each jug so that they float. You do this by attaching identical styrofoam bars to the top of each piece of clay. You place them in the jugs. Will the water levels in the jugs remain equal? If not, which one will now be higher? (Answer: The water levels remain equal; see Panel 2 of Figure A1.)

Problem 3. I have been given two pieces of clay that are the same size and weight. I mold one into the shape of a rod and the other into a ball. I have also been given two buckets that are equally full of water so that their water levels are the same. I am told to place the pieces of clay into the buckets so that they float. To do this, I obtain two identical bars of styrofoam. I attach the first piece of styrofoam to the top of the rod with a strong adhesive. I then attach the second styrofoam bar to the bottom of the ball. I now place one in each bucket of water and see that they float. Will the water levels still be equal? If not, which one will be higher? (Answer: The water levels remain equal; see Panel 3 of Figure A1.)

Problem 4. Mr. Jones and Mr. Smith are each given a piece of aluminum. These pieces are the same size and weigh the same amount. Both Mr. Jones and Mr. Smith decide to make toy boats. They bend their pieces of aluminum to make 2 differently shaped boats (see Panel 4 of Figure A1). They now want to test the ability of their boats to float. Both are given identical tubs filled with the same amount of water so that the water levels are equal. They place their toy boats in the tubs and find that they both float. Will the water levels of the tubs still be equal? If not, which one will now be higher? (Answer: The water levels remain equal.)

Complex

Problem 1. I have two cork cubes. They are the same size and weight. I place the first cork cube into a vice and compress it. I turn it sideways in the vice and compress it again. It is now much smaller than the other cork cube, but it is still in the shape of a cube. I also have two cups each filled with 0.25 l of water so that the water levels are equal. I place one cork cube in each cup. The larger one floats, but the smaller one sinks. Will the water levels of the two cups remain the same? If not, which will be higher? (Answer: The cup with the floating cube will have a higher water level.)

Problem 2. Two young boys, Bob and Joe, are each given a piece of aluminum that weighs the same and is the same size. The boys decide to have a contest to see who can make the best boat. Bob shapes his aluminum into a flat boat while Joe makes a pointed boat. Next, they get two tubs that are the same size and shape. They put the same amount of water in the tubs so that the water levels are equal. They then place one boat in each tub. Joe's boat sinks, but Bob's boat floats. Will the water levels in the tubs still be equal? If not, which one will be higher? (Answer: The tub with the floating boat will have a higher water level.)

Problem 3. The bolt-in-the-boat problem.

Problem 4. I have two toy boats that are identical in size, shape, and weight. Both have plugs in them so that water can be let into them. The plugs are attached to the boats by chains so that even when the plugs are pulled out of the boats, they stay with the boat. I also have two tubs identical in size, shape, and weight. Each are filled with 1 l of water. I place one boat in each tub and notice that the water levels are equal. I decide to sink one of the boats, so I pull the plug out of the boat. It eventually sinks. Will the water levels of the two tubs still be equal? If not, which will be higher? (Answer: The tub with the floating boat will have a higher water level.)

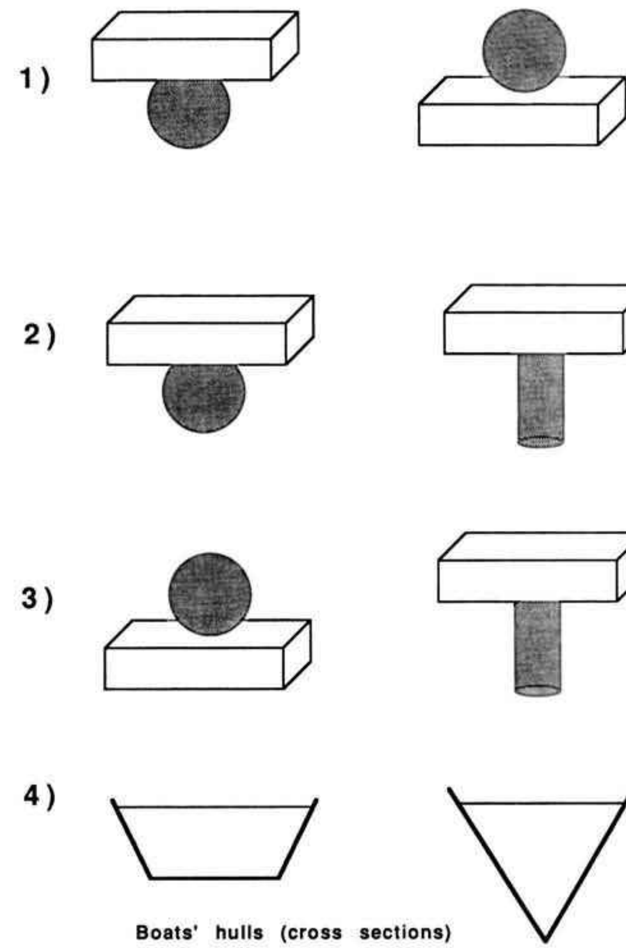

Figure A1. Diagrams shown to subjects in Experiment 3A to illustrate pseudocomplex displacement Problems 1–4.

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