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OBSERVER PROPERTIES FOR UNDERSTANDING DYNAMICAL DISPLAYS: CAPACITIES, LIMITATIONS, AND DEFAULTS

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SUMMARY

People's ability to extract relevant dynamical information while viewing ongoing events is discussed in terms of human capacities, limitations, and defaults. A taxonomy of event complexity is developed which predicts which dynamical events people can and cannot construe. This taxonomy is related to the distinction drawn in classical mechanics between particle and extended body motions. People's commonsense understandings of simple mechanical systems are impacted little by formal training, but rather reflect heuristical simplifications that focus on a single dimension of perceived dynamical relevance.

1. INTRODUCTION

In the past decade, advances in microprocessor technology have made dynamic visual displays technologically feasible. Display designers have been quick to embrace these new technologies, resulting in a commonly held belief that motion serves to enhance the informational content of visual displays. However, insufficient attention has been paid to the perceptual characteristics of the operators utilizing these displays. In this paper, we will discuss how the information carried in the motion of displays is defined and constrained by the capacities, limitations, and defaults the human observer brings to the situation. We conclude that the efficacy of motion information in visual displays is defined and constrained by observers' perceptual characteristics.

We will describe our research program which investigated people's commonsense understandings of simple mechanical systems, focusing on how these understandings were formed by direct observation of ongoing events. The types of mechanical systems studied consisted of very simple object motions, of the sort described in the first half of an introductory physics textbook. Thus, we examined such mechanical systems as pendulums, two-body collisions, gyroscopes, and fluid displacements. For all of these events, a sufficient amount of information was present for observers to make accurate dynamical judgments. Based on such kinematic analyses, some researchers (e.g., Runeson and Frykholm, 1983) have proposed that observers should be fully competent at extracting dynamical information from visual displays. However, we found that people's ability to construe dynamical events was highly constrained and that accurate judgments were made for only the simplest of events.

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We developed a theory of dynamical event complexity and tested many of its implications. In essence, we found that people can adequately construe dynamical events only when they can base their judgments on a single object parameter. In all other cases, their judgments are extremely muddled. We not only examined naive subjects, but also people with a great deal of experience with the systems about which they were being tested. These individuals included college professors of physics and high school physics teachers. It was found that these experts differed little in their common sense intuitions about dynamical systems and produced the same sorts of errors as naive subjects.

The implications for this work are clear. If graphical displays are to present dynamical information to operators effectively, then operator characteristics must be taken into account. Moreover, training operators to interpret natural dynamics is likely to be very limited in effectiveness.

The perceptual and cognitive properties of the human observers consist of three components: (1) capacities define the abilities of an operator to extract accurate dynamical information from a variety of contexts, (2) limitations specify the constraints on human dynamical information processing, and (3) defaults are the intrinsic assumptions that the operator is forced to use when unable to obtain the necessary dynamical information from direct observation. Each component is discussed in turn.

2. CAPACITIES

The field of dynamics deals with the causal necessity of object motions. It treats such properties as forces, i.e., the accelerations of masses. Since motion provides the only optical information upon which dynamical judgments could be based, judgments about such properties as mass must rely on dynamically constrained regularities in object motions.

Consider an intuitive example. Suppose that two balls of unequal mass are free to roll on a smooth surface. How might one ascertain their relative mass without picking them both up? One solution would be to roll one ball at the other, and if the collision resulted in the striking ball ricocheting back, then that ball is obviously the lighter of the two. Not only can qualitative judgments about relative mass be extracted from observing collisions, but in principle, the relative mass of the two balls is uniquely defined by the relative velocities of the balls following the collision. (The laws of energy and momentum conservation state that the mass ratio of the balls is equivalent to the ratio of their projected velocities onto an axis orthogonal to the path of the striking ball.) Similarly, there exist regularities in the motions of all mechanical systems that specify aspects of their dynamics. The human factors question is to determine the extent to which people can extract these dynamical properties when viewing events.

2.1 The Influence of Animation on Dynamical Judgments

In some contexts, viewing ongoing events results in quite accurate dynamical intuitions. This fact is especially striking when these judgments are at odds with people's expressed beliefs. Recently, a large number of investigations have been published that summarize commonsense beliefs about dynamics. These studies on dynamical understandings, termed "Intuitive Physics" by McCloskey (1983), showed that people often express erroneous beliefs about simple object motions when assessed in static, paper-and-pencil contexts.

Kaiser and Proffitt (Kaiser, Proffitt, Whelan, and Hecht, 1990; Kaiser, Proffitt, and Anderson, 1985) investigated most of McCloskey and his colleagues' situations by asking people to make judgments using paper-and-pencil examples, and when viewing animated, computer-graphics simulations of these events. The previous results were replicated for the paper-and-pencil problems. However, it was found that when viewing dynamic displays, people consider simulations of their erroneous predictions to be anomalous, and select natural motions as being correct.

Consider, for example, the pendulum problem in which subjects are asked to draw the trajectory of a pendulum's bob after its tether breaks at the instant when the bob was at the apex of its arc. Most erroneous responses predict that the bob will fall along a parabolic path rather than straight down. Now, at the instant that the bob is at its apex, it is stationary. Ask anyone what happens when a stationary object is dropped and they will predict a straight-down trajectory. The difficulty that people have with the pendulum question clearly involves their inability to construe the state of the bob's motion at the instant when the tether breaks. When viewing the ongoing event, the object's two motion states—swinging versus falling—are clearly separated in time. This segregation aids observers' judgments; when they see the anomalous outcome, they recognize it is not physically possible.

2.2 Motion Sensitivities

As is discussed in the next section, even when viewing ongoing events, people have an exceedingly poor appreciation for the dynamical significance of rotation. This could be due to two possibilities. First, it might be that the human visual system is not able to discriminate angular velocities as well as it can linear ones. A second alternative would allow for equivalent linear and angular sensitivities, but different processing capabilities at a deeper level.

Kaiser (1990) found that angular velocities are discriminated very well—not quite as well as linear velocities, but close. This implies that our poor appreciation for rotational dynamics cannot be attributed to an insensitivity to the relevant motions. Since the source of differential appreciation for linear and angular dynamics is not in a differential sensitivity to these motions, it must be the case that the perceptual system uses angular kinematics for a purpose other than dynamical analysis. We have suggested (Proffitt, Kaiser, and Whelan, 1989) that this purpose is form specification. Motions about the configural centroid tell us what an object is; motion of the configural centroid tell us where the object is going.

3. LIMITATIONS

The limitation that people exhibit when interpreting dynamical events, even when they are able to view the ongoing event, relates to the number of object parameters that must be represented in a dynamical representation. The simplest events require only that an observer notices the position over time of the object's center of mass. Most events, however, require that other aspects of the object be noticed as well and integrated. Yet, the complexity of these events exceeds our ability to perceptually penetrate their dynamics. This account of dynamical event complexity is detailed in Proffitt and Gilden (1989). We summarize it below.

3.1 Particle and Extended Body Motions

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 properties that are relevant to interpreting its motion. For particle systems, only the motion of the object's center of mass is relevant to its dynamics. For extended body systems, mass distribution, orientation, rotation, and other properties are dynamically relevant variables. It is important to keep in mind that the relevance of object properties depends not on the object itself, but on the motion context in which the object is observed.

Consider the two following contexts for the motion of a top: (1) Free fall of a top that has been dropped in a gravitational field, and (2) 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 trajectory of the center of mass of a spinning top in free fall is identical to that of a nonspinning one. On the other hand, a 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; a spinning top falls sideways—that is, it precesses. Thus, spinning tops have many more dynamically relevant features.

Dynamical analyses of particle motions are much simpler than are those of extended body motions. This is due to the increased number of variables that must be included in an adequate dynamical representation of extended body events. Particle motions can always be understood in terms of center-of-mass displacements. Dynamical representations of extended body motions always relate more than one category of information. In extended body motions, it is not sufficient to know where an object's center of mass is located. Rather, such relational properties as mass distribution—how much of the object's mass is located where—must be appreciated. Thus, relating different categories of information requires multiplicative processes and results in multidimensional quantities that do not relate directly to categories of perception.

3.2 Adequate Dynamical Understandings are Limited to Particle Motion

Commonsense understandings are fairly good for particle motions. Although people sometimes make erroneous judgments in pencil-and-paper contexts, their dynamical intuitions are quite accurate when they actually observe the ongoing events (Kaiser, Proffitt, Whelan, and Hecht, 1990). However, when people attempt to form dynamical understandings of extended body motions, dynamical competence begins to break down in both static and ongoing contexts. This can be seen in the way people understand the dynamics of simple angular systems.

We conducted a large-scale investigation of commonsense understandings of the dynamics of rolling wheels and gyroscopes (Proffitt, Kaiser, and Whelan, 1990). An example of one of the questions asked in this study was: What influences the rate that a wheel will roll down an inclined plane—its radius, mass, or mass distribution? In fact, the participants of this study were not asked this question directly. Rather, they were shown pairs of wheels that differed on one of these dimensions and asked to predict which member of the pair would roll down the ramp in the least time, or whether both wheels would roll at the same rate. The results of this study showed that people are somewhat unsure about the influence of radius or mass on a wheel's rolling behavior, but generally agreed that mass distribution (one wheel was a solid disk and the other a rim) was irrelevant. The multidimensional quantity of moment of inertia that describes mass distribution was the only relevant dynamical variable in this situation; however, it was virtually ignored.

Next, we assessed an observer's implicit dynamical appreciation of moment of inertia by creating an animated computer graphics display consisting of a satellite spinning in space. This satellite was constructed solely out of solar panels that could open or close, thereby affecting the satellite's moment of inertia. (This situation is analogous to a twirling ice skater who extends or contracts his/her arms.) In a natural situation, opening the satellite's solar panels would cause its spinning rate to slow, whereas closing the panels would result in an increase in angular velocity. In the animated stimulus displays, opening and closing the panels resulted in a variety of spin rates. The observer's task was to judge whether the resulting angular velocity was the natural outcome of the satellite's changing shape, or whether it could only have been produced by some unseen force. Subjects made highly qualitative judgments about the influence of changing shape on angular momentum. For the cases in which the satellite's solar panels opened, they judged the following outcomes to be unnatural without an external force: (1) The satellite stops and reverses its direction of spin, or (2) the satellite simply stops. All other outcomes were judged to be equally natural. In addition to the natural slowing rate, these other outcomes included a situation in which the satellite's angular velocity remained unchanged, one in which it actually sped up, and two in which the spinning rate slowed, but by an incorrect amount. Equivalent results were obtained when the satellite closed its solar panels. Clearly, these subjects demonstrated only the most rudimentary understanding of the influence of mass distribution on angular momentum.

Studies performed in conjunction with those on understanding wheel dynamics showed that people have very poor comprehension of gyroscopic motions in at least two respects. First, they do not realize that everyday objects with which they have interacted behave like gyroscopes. This was found to be the case when they were questioned about the behavior of bicycles. Even a group of bicycle racers showed little awareness of the gyroscopic properties of their bicycles. Second, when viewing a spinning gyroscope, people exhibit amazement, but no comprehension of what prevents the gyroscope from falling over.

3.3 Formal Training Does Little to Influence Immediate Intuitions about Extended Body Dynamics

The study described above was repeated with a group of 20 high school physics teachers (Proffitt, Kaiser, and Whelan, 1990). It was found that their commonsense understandings of angular systems did not differ from those of the unsophisticated students. Although these teachers could solve the problems analytically (if given time and writing materials), they failed to evidence any benefit from years of instructing others about these simple mechanical systems when forced to rely on their immediate intuitions.

In addition, more informal tests were performed with university physics professors. Again, when these individuals were asked to respond quickly and were prohibited from writing down the relevant equations, their responses differed little from those of naive subjects.

We conclude that expert knowledge about dynamical systems does not penetrate commonsense intuitions. Physicists and physics teachers share with naive individuals a sense of befuddlement about the types of extended body motions that we examined. Learning physics does not involve a restructuring of commonsense. Rather it is concerned with a change in the domains of understanding—a shift from the phenomenal world to the formal world of physics theory. Even if it is not possible to see what is going on with a rolling wheel, it is easy to "see" what is going on with its mathematics.

4. DEFAULTS

Research on people's ability to interpret extended body motions revealed the following propensities.

4.1 Particle Motion Bias

People tend to treat extended body systems as if they were particle motions. That is, extended object properties are deemed to be irrelevant and judgments are based solely upon center of mass dynamics. We have proposed that the source of this bias is intrinsic to the perceptual organization of motion information (Proffitt, Kaiser, and Whelan, 1990).

In perceiving rotational motions, the perceptual system performs an analysis that emphasizes the extraction of form at the expense of recovering information needed for dynamical analyses. Consider wheel-generated motions. Every point on a rolling wheel follows one of three possible classes of motion paths: cycloids, prolate cycloids, or straight lines. When viewing a rolling wheel, however, these trajectories are not seen. Rather, the perceptual system analyzes motion into two components:

(1) Relative rotations—all points are seen as revolving about their configural centroid, and (2) a common motion which is the trajectory of the centroid (Proffitt, Cutting, and Stier, 1979).

Relative rotations are not only separated from common motions, but also these two motion components have quite different perceptual significances: Rotations specify form, whereas common motion defines displacement relative to the observer. The perceived common motion is the motion path of the centroid of relative rotations. Under the assumption of uniform density, this centroid corresponds to the form's center of mass. Thus, the perceived motion of the whole object—its common observer relative displacement—is a particle motion.

In essence, we propose that the perceptual system performs an analysis that extracts rotational motions for the purpose of recovering form. Common motions are used to define particle motion dynamics. Thus, the only motion that is available for dynamical analysis is common motion. Consequently people show perceptual competence for dynamics only when the relevant motions are those of an object's center of mass, and the only relevant object motions for dynamical intuitions are particle motions.

4.2 Heuristics

In some extended body motion situations, people may be aware that more than one dimension is of dynamical importance; however, they do not combine this information into an appropriate multidimensional representation. Rather, they employ implicit heuristics, each of which relates to one of the dynamically relevant dimensions in the event and ignore the rest. A clear example of this type of reasoning can be seen in how people dynamically evaluate collisions (Gilden and Proffitt, 1989).

Imagine a situation in which there are two billiard balls of unequal mass, and one of these balls, being initially stationary, is set into motion when it is struck by the other. An analysis of the physical laws of momentum and energy conservation reveals that the post-collision projected velocities of the two balls onto an axis orthogonal to the pre-collision path of the striking ball defines a ratio equivalent to their relative masses.

When asked to judge mass ratios while observing computer simulations of collisions, people do not spontaneously form this multidimensional relationship between velocities and angles. Rather, they base their judgments on one or the other of two heuristics that relate to these dimensions. The velocity heuristic can be stated as: Following a collision, the faster moving ball is lighter. The other heuristic relates to deflection angle: After a collision, the ball that ricochets is lighter. People based their relative mass judgments on the heuristic that was related to the most salient dimension present in the event (i.e., either velocity or deflection angle). In many situations such heuristical analyses led to good performance. However, when the two heuristics give conflicting predictions, performance falls to the level of chance. Moreover, subjects never "averaged" the ricochet heuristic with the velocity heuristic to effect a compromise.

We found that people have difficulty switching from one heuristic to another. This problem was revealed in a set of studies conducted on people's commonsense understandings of Archimedes Principle (Kaiser, Proffitt, Whelan, and Hecht, 1990). Here, it was found that people could make accurate judgments about fluid volume displacements only when judgments could be based on one object parameter.

Consider the following question adapted from Walker's (1977) book, The Flying Circus of Physics with Answers: Suppose that a toy boat is placed into a fish tank. A heavy bolt is put into the boat, and the water level in the tank is marked. If the bolt is removed from the boat and dropped into the fish tank, then what will happen to the height of the water level with respect to the previous mark?

If the questions asked of university students about fluid displacement required them to reason about one object parameter at a time, then their performance was nearly perfect. This leads to the assumption that they had a thorough understanding of Archimedes Principle. An example of a one-dimensional question is the following: Two objects of different weight are observed floating in identical fish tanks; which object displaces the most water? On the other hand, if they were asked a question, such as the above bolt-in-the-boat question, then their performance fell to a chance level. (In this question the bolt must be construed as a multidimensional entity: Its mass is relevant while it is in the boat; however, its volume becomes its relevant dimension when it is placed in the water.) Most people erroneously reported that, when the bolt was put into the tank, the water level would remain the same as it had been when it was in the boat. Similar performance was found for other questions that required an object to be construed as having more than one dynamically relevant dimension.

We constructed a tank in which the water level could be rapidly raised or lowered by the experimenter at the moment when the bolt was placed into the tank. Subjects were presented with a toy boat floating in the tank. A heavy bolt was placed in the boat. They were told that the bolt would be taken out of the boat and placed in the tank's water. They were also told that the water level might be raised or lowered by the experimenter. Their task was to watch pairs of events and determine whether the tank's water level had been influenced by the experimenter. In this situation, observers reported that the natural event looked correct, and that their own prediction (i.e., the water would rise to its original level after the bolt was removed from the boat and placed into the tank) looked highly contrived.

The superior performance that was observed with a demonstration of the problem, relative to the verbally presented task, is a general finding in many situations that we have investigated. Often, the dimensionality of events are segregated in time when an event is observed; observing the bolt as it was taken out of the boat allowed the subjects to see how this heavy object produced a large displacement. Observing the small bolt being placed into the tank, and watching the water level rush back to its initial level, induced considerable mirth, as the bolt's size had then become so salient. In this displacement problem, the dimensions of weight and size are separated in time in the ongoing event, but not in the verbally presented question.

4.3 Kinematic Representation for Apparent Motion

A basic default in observers' motion processing is the representation given to ambiguous motions. Following Shepard (1984), we found evidence suggesting that apparent motions are given a kinematic, as opposed to a dynamical, representation.

We investigated apparent motion trajectories for stimuli flashed in different locations and at different orientations (Proffitt, Gilden, Kaiser, and Whelan, 1988). The fact that this event involved an orientation change defines it as being an extended body motion. There exist two theoretically motivated alternatives for the apparent trajectories that could be seen. (1) The stimulus shape could follow a single rotational trajectory defining the minimum motion for a kinematic representation of this event (Foster, 1975). A kinematic representation treats the situation purely in terms of motions, disregarding dynamical considerations. (2) For the other alternative, the stimulus could be seen to rotate about its center of mass (which corresponds to the centroid for forms of uniform density) as this point moved linearly. This alternative represents a dynamical minimization of energy (assuming that the stimulus has some mass and is otherwise unconstrained with regard to its potential motion paths). It was found that apparent extended body motions followed curved paths; however, these perceived trajectories were actually circular (i.e., pure kinematic trajectories) for only a restricted range of parameters. Hecht (1989) extended these findings to objects that are perceived to change orientation about an axis that is not normal to the picture plane (i.e., rotations in depth).

These results incline us toward the view that observers represent object motions in the form of a kinematic, rather than dynamic, model. The resulting kinematic variables form the bases for heuristics that structure dynamical intuitions.

5. CONCLUSION

People spontaneously extract a variety of environmental properties from motion information, a fact that can be exploited through the increased use of animation in computer graphic displays (Kaiser and Proffitt, 1989a, b; Proffitt and Kaiser, 1989). On the other hand, there are limits to the veracity of motion-based intuitions that become evident when they make judgments about natural dynamics.

People's dynamical understandings are fairly good for particle motions. Although people sometimes make erroneous predictions about these simple systems in paper-and-pencil contexts, their dynamical judgments are quite accurate when they observe a demonstration of the dynamic event. Again, this emphasizes the desirability of animation for displaying particle motion dynamics for purposes of instruction or system monitoring.

When people attempt to form dynamical understandings of extended body motions, dynamical competence breaks down. In these contexts, competence is best when the operator can deal with one dimension of information at a time. The implicit knowledge that people possess about extended body systems is heuristical, but each heuristic relates to only one dimension of information.

Formal training in physics does little to improve spontaneous intuitions about natural dynamics. If operators are to be required to make rapid judgments about dynamics, then they would be better equipped if their training provided them with a set of heuristics relevant to frequently encountered situations, as opposed to more formal training in physics.

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16. Abstract

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