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On the Origins of Dynamical Awareness

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An inquiry into the origins of dynamical awareness is conducted. Particular attention is given to a theory that postulates that impressions of dynamical quantities are derived from and structured by lawful physical relations. It is shown that impressions of dynamical quantities are not generally correlated with the values that these quantities take in the equations of motion but rather are highly correlated with simple ratios of kinematic quantities or with specific kinematic features that do not specify the underlying dynamics. It is argued that kinematic information, to the extent that it is used, is used heuristically, and its availability for dynamical analysis is constrained by general principles of organization. A formal analysis of the physical organization implicit in the specification of dynamical invariants is given and compared with types of perceptual organization that are observed.

The development of a framework for understanding what perceptual organization is and how it is achieved is a central issue in perception. Information theory (Shannon, 1948) has provided a language for describing what perceptual organization accomplishes and has focused attention on the sentiment that information is, in some sense, the material of perception. The relationship between perception and information has been particularly stressed in the ecological approach (Gibson, 1979) through the twin notions that information is available in the environment of a perceiving animal and that perception itself is the pickup of useful information. The information-theoretic aspects of perception should, however, not be identified with ecological psychology; all fundamental theories of perception must reckon with the basic observation that perception is meaningful. Perceptual organization, whether it is mediated by pragnanz (Kohler, 1947), contingent on intelligent inference (Helmholtz, 1910/1962; Rock, 1983), or concomitant to so-called direct perception (Gibson, 1979), is at root the pickup of information through the reduction of ambiguity in proximal stimulation.

Psychology is not the only discipline that is struggling with the development of organization. This is a major problem in biology (see Oyama, 1985; Rosen, 1978), and is the focus of the science of dynamical systems that has application in virtually every field that studies the evolution of systems in time. Ideas from dynamical systems, in particular the origin and structure of chaos, are reshaping basic conceptions of the physical world with an impact that has been equaled only by the advent of Newtonian mechanics, relativity, and quantum mechanics. The critical difference between the approaches to organization in psychology and in physics is that in the latter there appears to be a framework for posing the problem. The amount of information in a physical system and the rates of its destruction and creation can be calculated using a variety of schemes (Guckenheimer & Holmes, 1983; Shaw, 1981). The quantification and characterization of perceptual uses of information are inextricably bound in a myriad of unresolved issues in measurement and representation (Rosen, 1978).

Recently it has been argued that there is a special province in which the acquisition of information can be described within a systematic psychological theory. This province consists of the dynamical impressions that are attendant to the perception of natural and animate motions. The theory that has received the most complete exposition contains as its central theme that kinematics specifies dynamics (KSD; Runeson, 1977). KSD theory is allied with the ecological approach in its emphasis that dynamical information is ambient in the environment and that this information is revealed by specific motion patterns in the optic array. It is also distinguished from other theories that address the perception of motion by its realism; the laws of physics provide the context in which specification takes place.

KSD can be contrasted with a broad class of theories that hold that the perception of motion is subject to protocols that are not constrained by natural law. A prime example of this class is Shepard's theory of internalized constraints in which motion perception is structured by kinematic geometry (Carlton & Shepard, 1990; Shepard, 1984). Ramachadran's notion that perception is a "bag of tricks" (1990) also falls into this class. This latter position is roughly that perception operates heuristically without resort to systematic or coherent principles in order to achieve specific evolutionary ends. Although I do not wholly embrace either of these positions, the arguments that I make in this article share the same conceptual grounding—that perception has its own logic and that this logic is articulated in part by the forms of dynamical awareness.

In this article I examine three classes of studies that have been taken to be experimental confirmation of KSD: the specifications of relative mass and elasticity in a two-body collision, and the specification of weight by the act of lifting. A careful examination of the results from these studies will demonstrate

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that although it is clear that motions are perceptually organized in a number of ways, KSD is not a viable theory of their organization. In each case I will show that what was thought to be experimental evidence in favor of a KSD interpretation is, in fact, more compatible with an interpretation that has as its basic theme that dynamical awareness arises from a heuristical understanding of motion—a position not unlike Ramachadran's.

The second part of this article investigates the origins of dynamical awareness. A comparison of the physical organization of motion events with the organizations that are exemplified by the structure of human judgment will clarify to a large extent the ways in which kinematic information is, in fact, used. I will argue that motion events are perceptually organized as having extent in time and that contrary to the notion that perception is a "bag of tricks," event segmentation in time is geometrically similar to image segmentation in space. This inquiry will attempt to account not only for those events for which people have impressions of dynamics, but also for those domains where such impressions are lacking. Finally, I will argue that successful theories of dynamic awareness must take account of how decisions are made on variables of one type and across types. Although it may appear to be a step backward, the development of these theories will require illumination of basic issues in the representation and measurement properties of kinematic variables.

Specification of Dynamics Through Kinematics

Kinematics refers to the changes in the optic array that occur when an object moves. All concomitants of displacement in time are within this domain. Spatial position, velocity, acceleration, and all other orders of derivatives of a motion path may be regarded as kinematic variables. The point of departure for KSD is that the perception of a motion consists of impressions that cannot be described using only the language of kinematics. In the domain of natural motions there are impressions of causation, weight, and other dynamical factors that are implied by but are not part of a kinematic description. For example, the studies by Michotte (1963) on the perception of causation illustrate how certain patterns of acceleration are accompanied by the definite impression that the motion of one object was caused by its interaction with another. The implication of background, non-kinematic factors in animate motions is equally relevant here. For example, the motions of point-light walkers can reveal intentionality and gender (Cutting, 1978; Cutting & Kozlowski, 1977; Runeson & Frykholm, 1983). In all of these cases, there is no question that motion perception is not limited to a purely kinematic description.

KSD goes beyond the recognition that kinematic variables cannot describe the perception of motion by attempting to establish a coherent link between impressions of dynamics and their kinematic support. The key element of KSD is that this link is given by the lawful relations in physics that supply the mapping between kinematic and dynamical variables. Versions of KSD differ primarily in terms of their claims of veridicality of these dynamical impressions. The strongest version of KSD is simply that when the kinematics uniquely specifies the dynamics, then the dynamics is, in fact, recovered by human observers. The majority of experiments that have been motivated by KSD test this particular version. Weaker forms of KSD postulate that recovery is possible up to the limits of normal terrestrial experience (Warren, Kim, & Husney, 1987). This weaker form is obviously much more difficult to test without a prior account of the content of terrestrial experience. The weakest form of KSD (Bingham, 1987) is that if there is a unique mapping between kinematics and dynamics, then kinematic patterns provide a useful source of information about the underlying dynamics. This version essentially eviscerates the motivation for KSD in that it is not a theory of human performance and really has no psychological content. What psychologists want to know is how kinematic information is, in fact, used by people, not the utility of this information for an ideal device.

KSD is best introduced by reviewing an initial application (Runeson, 1977) in the context of collision dynamics. Consider the relation between the optical pattern of velocities in a collision and the nonoptical dynamical invariant of mass ratio. Runeson (1977) noted that one could rewrite the equation for momentum conservation,

$$m_1 v_{1i} + m_2 v_{2i} = m_1 v_{1f} + m_2 v_{2f}, \qquad (1)$$

so that the masses (m_i) were all on one side and the velocities (v_{ij}) on the other (1 and 2 are names for the colliding objects and i and f refer to initial and final velocities, respectively):

$$m_1/m_2 = (v_{2f} - v_{2i})/(v_{1i} - v_{1f}). \qquad (2)$$

As a statement about physics, Equation 2 is a trivial rewriting of the conservation law. However, interpreted as a statement about human performance, it contains the core content of KSD. As a statement within KSD, this expression has the following meaning:

1. The kinematic pattern in a collision consists of the initial and final velocities for both objects.
2. All primitives that refer to the kinematics can be written by themselves.
3. An expression written entirely in terms of kinematic primitives can be equated to an object that is not itself a kinematic term—the mass ratio.

As a psychological statement, KSD asserts that the kinematics, in this case, uniquely specifies the mass ratio, and that this mapping serves as the basis of the perception of mass ratio.

There are a variety of ways in which the displayed mapping between velocities and mass ratio could be useful in terms of understanding the manifest experience of heaviness that does occur when two things collide. The best case for KSD would be that human observers accurately perceive mass ratios and that parametric variations in the velocities lead to just the right variations in the perception of mass ratio, as would be predicted from momentum conservation. A slightly worse case would be that observers are accurate in only certain regimes of kinematic variation, but that the recovery of mass ratio still seemed related to momentum conservation. The falsehood of KSD would be shown if it were demonstrated that judgments of mass ratio had nothing to do with momentum conservation, and that the lawful mapping in the physical domain that is supposed to provide useful information was entirely irrelevant to observers. As shall be shown, Runeson's (1977) own example provides the clearest case for the invalidation of the KSD principle. In what follows, I shall examine a number of experimental paradigms that assess the utility of KSD as a principle of human performance. In all cases, I shall argue that KSD is either wrong or unsupported by the data.

Assessments of Impressions of Dynamics: Three Case Studies

The Perception of Mass Ratio

Runeson (1977) suggested that the perception of mass ratio in a two-body collision would be an ideal test bed for the KSD principle. Subsequently, several groups conducted formal experiments to ascertain whether human subjects could, in fact, make reliable estimates of mass ratio in collisions. Although the initial results looked promising, Gilden and Proffitt (1989) showed conclusively that the lawful mapping between kinematics and dynamics that is supplied by momentum conservation had no relevance to human judgment. In what follows, I will trace the recent history of this problem and demonstrate the inadequacy of KSD as a theory of what people are doing when they assign mass ratios in a collision.

Todd and Warren (1982) conducted the initial studies. The collisions they looked at were head-on in one dimension; movement was confined to a straight line path. Their experiments consisted of two motion conditions and three levels of elasticity. In what follows I will concentrate only on the most elastic collisions ($e = 0.9$), because the perception of elasticity is a separate issue and will be discussed in detail in the next section. In a first experiment, the two objects approached each other at a range of relative speeds and collided, and the subjects made estimates of mass ratio. The data were encouraging: Accuracy in determining which of the objects was heavier was an increasing monotonic function of the absolute value of the mass difference. This makes sense because as the mass ratio approaches unity, any system with internal noise would be expected to make increasing errors. In a second experiment the objects either approached each other with constant speeds or one of the objects was initially stationary. In the approach condition, performance in distinguishing the heavier object was uniformly excellent (correct responses always exceeded 89% and were generally near ceiling) and showed the same monotonicity with the mass difference magnitude. Performance in the stationary condition was not so good and indicated that there might be more to this problem than considerations of the constraint imposed by momentum conservation. I will return to a discussion of this condition later.

Further evidence of accuracy in judgments of mass ratio was found by Kaiser and Proffitt (1984) in a developmental study. Children (kindergarten through fourth grade) could reliably judge which of two objects was heavier in a collision and could distinguish collisions that conserved momentum from those that did not. Kaiser and Proffitt (1987) went further and showed that judgments of mass ratio did not change when frictional forces were added to the simulation; observers did not show a bias toward terrestrial realism. They concluded that observers have a general competence in the perception of this dynamical invariant that is not constrained by terrestrial experience. Subsequent references to the judgment of mass ratio (Runeson & Frykholm, 1983; Warren et al., 1987) appear to regard the case for KSD as having been made.

Todd and Warren (1982) noted that several of their observers reported in debriefing sessions that the slower moving object, following collision, looked heavier. Although self-reports do not indicate the nature of perceptual processing, this statement is telling in that it suggests that observers might be using kinematic information heuristically, as opposed to using it as input to a momentum conservation constraint. This is an important distinction. Heuristic usages of information are not compatible with the principle of KSD. A heuristic reveals an idea, generally one formed from experience, that is used to organize an event. This organization may be consistent with the lawful relations in physics, in which case it could not be distinguished from KSD. However, a heuristic need not bear the same parametric relation to kinematic variables as a conservation principle, and there may be opportunities for distinguishing KSD from heuristic processing on this basis. The odd performance in Todd and Warren's (1982) study, where one ball was initially stationary, provides such an opportunity.

Todd and Warren (1982) attempted unsuccessfully to find a single heuristic that could explain the pattern of data in their stationary condition. Their failure can be traced to their assumption that a single heuristic would suffice. As I shall argue subsequently, observers use a second heuristic in judging mass ratio: A ricocheting object looks lighter than the object it struck. Evidence for this second heuristic is implicit in Todd and Warren's own data, shown in Figure 1.

To understand how observers judge mass ratio in one-dimensional collisions, it is useful to pay attention to how these collisions appear. Particular notice should be paid not only to the magnitudes of the postcollision velocities, but also to their directions. The ratio of postcollision velocities, when one ball is initially stationary, is given by

$$v_{2f}/v_{1f} = 2/(1 - m_2/m_1).$$

The velocity ratio, v_{2f}/v_{1f}, is also shown in Figure 1, and it is clear that this ratio is highly correlated with performance. This

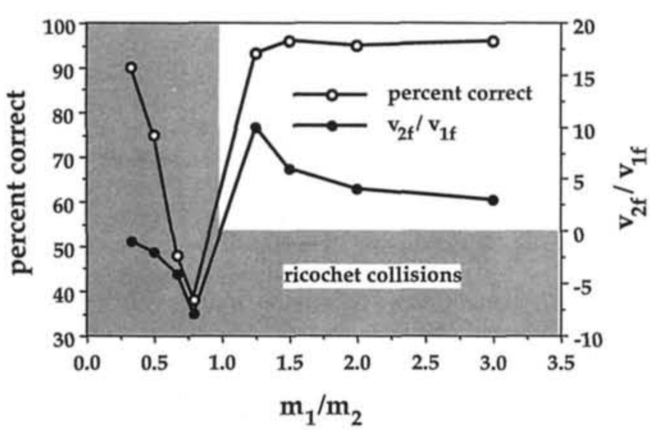

Figure 1. Percentage correct data from the stationary condition for the collision of two elastic balls (Todd & Warren, 1982) shown together with the ratio of exit velocities. (The correlation between the velocity ratio and percentage of correct responses discriminating which ball was heavier reveals the existence of two heuristics in judging mass ratio.)

correlation can be understood as follows. When the incoming ball is much heavier than the stationary ball ($m_1 \gg m_2$), then the stationary ball gets "clobbered" and its high postcollision velocity makes it appear less massive. Because it is, in fact, less massive, observers are able to make this distinction with high accuracy. When the converse holds, $m_1 \ll m_2$, the incoming ball ricochets, and the magnitude of its postcollision velocity is much larger than the forward motion of the ball that was struck. Here the subjects have two reasons for saying that the incoming ball was less massive; it is going backward following collision and its speed is also much greater than that of the struck ball. Accuracy in this regime also approaches ceiling. Now consider the situation where the incoming ball is only slightly less massive than the struck ball, say 30% to even 50% less massive. In this regime heuristic usage will lead to variable, possibly worse than chance, performance. Here the incoming ball ricochets backward, but its speed is much slower than that of the struck ball. It is the possibility of this type of behavior that makes collisions so useful for heuristic analysis: The heuristics can be brought into conflict. An observer using heuristics is in a quandary when both balls look less massive by different criteria. It is precisely in the regime where v_{2f}/v_{1f} is large and negative, as illustrated in Figure 1, that observers are unable as a group to decide which object is heavier. Apparently, some observers go with speed, whereas others go with ricochet.

Gilden and Proffitt (1989) developed this analysis in the context of two-dimensional collisions. In a series of experiments where an incoming ball struck one that was initially stationary, we were able to ascertain the nature of heuristic usage more confidently by having observers not only indicate which of the two objects was heavier, but also by having them rate the magnitude of the ratio. Our results can be summarized as follows:

1. Observers parse the event into speed along the trajectory and the angle of the trajectory. This parsing turns the construction of mass ratio into a much harder problem than it really is. An ideal observer would parse the event into the speeds orthogonal to the collision axis. The ratio of the projected speeds is proportional to mass ratio. Such an observer need not remember the speed of the incoming ball.
2. When the ricocheting ball moved slower than the ball it struck, the distribution of magnitude estimates was bimodal. Subjects always thought that the mass ratio was large (no one said the objects had equal mass), but they could not decide as a group which object was heavier. It can be seen here that, when presented with heuristic conflict, observers simply ignore one of the conflicting items.
3. By varying the impact parameter (how off center the collision is), we could vary the postcollision velocity ratio while holding the mass ratio constant. In a series of such collisions where there was no ricochet and both balls scattered forward, we found that estimates of mass ratio magnitudes correlated with the ratio of speeds, not with the underlying, constant mass ratio.
4. The incoming velocity is irrelevant information. When observers can reliably estimate which object is heavier, they are actually more accurate if the precollision epoch is masked.

This analysis presents a picture of human performance that is incompatible with KSD. There is no question that observers do generate vivid impressions of mass ratio, and that kinematic information is used to arrive at these impressions. To this extent, kinematics does specify dynamics. Furthermore, there is no question that momentum conservation principles do provide useful information. The crucial distinction in heuristic usage is that the heuristic specification is in no sense related to lawful mappings between kinematics and dynamics. The mapping that people apparently use is based on a small set of separate ideas that they have about the way the world works. The application of these ideas does not correlate with momentum conservation or any other physical mapping. Rather, the mapping is more of the following sort: The postcollision speed of the struck ball is really large, it really got clobbered; it must be much lighter. The issue here is ultimately concerned with the nature of perceptual organization. KSD holds that organization proceeds through lawful mappings. The evidence for heuristic usage shows that organization proceeds through an interpretation of the event that is mediated by informal understandings of the world.

The issue of perceptual learning is particularly relevant with regard to the judgment structures that are evidenced in the collision paradigm. Perceptual learning is a key part of Gibsonian theory—the discovery of new properties of the world by discovering new variables in the optic array. There is little doubt that perceptual learning plays a major role in the development of dynamical awareness. The heuristics that Gilden and Proffitt (1989) elucidated in terms of ricochet and clobbering perhaps should be viewed as the outcome of such learning. It must be recognized, however, that what is learned as a result of world experience with collisions are not KSD mappings, but just these simple heuristics. Furthermore, it is not a paucity of experience with collisions that focuses learning on heuristics. Adults presumably have sufficient experience with collisions, indeed with collisions attended by feedback, that the development of heuristics must be understood as a highly tutored outcome. The efficacy of perceptual learning is, in fact, illustrated by the extraordinary sensitivity that people have for the optical information in collision events. The strong correlation that Gilden and Proffitt found between speed ratio and estimated mass ratio shows that within the conceptual parsing of the collision event, people display a high degree of sensitivity to kinematic information. The fact that estimates of mass ratio often bear little relation to distal mass ratio arises from the bundling of these sensitivities within an organizational scheme that, although compelling, is simply not correct.

The role of perceptual learning is also relevant in the other experimental paradigms discussed in this article. In the contexts of the perception of elasticity and lifted weight, I will argue that people are highly adept at using kinematic information in support of dynamical judgments, and it may be that these abilities are the outcome of perceptual learning. The distinction between the sensitivity to kinematic information and the usage of such information will continue to apply. The way in which information is used depends fundamentally on the organizational scheme in which that information is embedded. KSD is but one possible scheme, and apparently not the one that is developed though natural experience. The central issue that arises, therefore, is not the existence of perceptual learning, but rather why kinematic events are perceptually organized in the manner that is observed.

The Perception of Elasticity

The coefficient of restitution, elasticity, is a property defined on pairs of objects that can potentially reveal itself in a collision.

Informally, elasticity is a measure of the fraction of kinetic energy that is lost to internal degrees of freedom through deformation. The elasticity is defined in terms of the ratio of pre- and postcollision velocity differences:

$$e = (v_{1f} - v_{2f})/(v_{2i} - v_{1i}).$$

From the perspective of KSD, mass ratio and elasticity have much in common; they are both specified by ratios of velocity differences. In fact, the expressions for mass ratio and elasticity are isomorphic under the replacement $f \leftrightarrow 1$ and $i \leftrightarrow 2$ (where $i \leftrightarrow j$ means substitute i for all instances of j and j for all instances of i). In this sense, elasticity is a dynamical invariant that is specified by an arithmetic combination of kinematic quantities, and so is potentially a candidate for recovery under the KSD principle.

There are, however, important distinctions between mass ratio and elasticity. The expression for mass ratio follows immediately from momentum conservation. The expression for elasticity derives from a much more complicated expression that refers to shear and strain tensors (although here the representations of these tensors constitute a diagonal matrix). Furthermore, mass ratio is related to mass, which is an unambiguous property of individual objects (at least within a given frame of reference). Elasticity, on the other hand, is not a property of objects per se; rather, it is a property of object pairs in collision. In addition, it is constant only within certain collision regimes. A metal object that bounces at low velocity may dent at high velocities. Denting will dramatically decrease the measured elasticity. Given these caveats, it is not clear whether elasticity is the best candidate for perceptual recovery within KSD. However, KSD has been applied in situations where the physical mappings are highly complex (in particular, perception of lifted weight), and experiments have been conducted within the spirit of KSD to determine whether elasticity is perceptually recovered by human observers.

The most complete set of studies that have addressed the issue of the perception of elasticity were conducted by Warren et al. (1987). In the experiments of interest here, the investigators had observers estimate the elasticity of animated displays of bouncing balls. Data were collected in the form of "bounciness" ratings. These data were analyzed in terms of their correlation with the distal elasticity values in the animations.

The kinematic information that specifies the elasticity of a bouncing ball is redundant, deriving from three different kinematic dimensions. First, elasticity is specified by the ratio of velocities, as noted earlier. In the case of ball–earth collision, the physics is somewhat simplified by treating the earth as stationary. In this case,

$$e = |v_2/v_1|,$$

where v_2 is the velocity just following bounce, v_1 is the velocity just prior to impact, and the absolute value has been taken. Velocities may be related to maximum height by noting that, between bounces, energy is conserved. This allows elasticity to be expressed in terms of the maximum height reached between bounces;

$$e = (h_2/h_1)^{1/2}.$$

Finally, elasticity may be written in terms of the durations of successive bounces because, for free-fall trajectories, the duration of flight is proportional to launch velocity:

$$e = \tau_2/\tau_1.$$

Warren et al. (1987) assessed the utility of the different sources of information in deriving impressions of elasticity by imposing masks on the animation so that in any display, two of the three sources were occluded. There was also a full information condition where observers were allowed to witness the entire animation without masking.

The data from Warren et al. (1987) showed that observers were unable to use velocity or duration information in the recovery of elasticity. Bounciness ratings were not significantly correlated with elasticity when only velocities near impact or durations between bounces were available. In the velocity condition, ratings were significantly correlated only with the magnitude of the postcollision velocity ($r = .70$), whereas in the duration condition, ratings were about equally correlated with the individual durations ($r \approx .76$). These results suggest that there may be perceptual limitations regarding velocities and durations that constrain the abilities of observers to form the appropriate ratios required for veridical impressions of elasticity. This apparent inability causes observers to base their impressions of bounciness on individual variables that do not specify elasticity. I will return to this issue later.

The finding that observers are unable to use two of the three available information sources does not, in itself, invalidate the KSD principle. KSD asserts that to the extent that recovery of dynamics is effective, the recovery is mediated by lawful relations in the world. However, this observation does vitiate the utility of KSD as a theory of human performance, because the distal sufficiency of information does not constitute a psychological principle; a useful theory must make predictions about how information is, in fact, used. This distinction is highlighted by the way observers made use of relative height information in the full information and height conditions.

In the animation condition, where only the maximum heights of each trajectory were visible, bounciness ratings were highly correlated with elasticity ($r = .87$). Furthermore, in debriefing, all of the subjects reported using relative height as a basis for their ratings. These results suggest that observers do, in fact, recover elasticity and that this recovery uses only the information that veridically specifies it. In the perception of elasticity, there does not seem to be heuristic usage of the sort encountered in mass ratio estimates where regimes of complete incompetence were encountered. However, this interpretation of the bounciness ratings can be shown to be grossly misleading by asking the simple question, What are the observers, in fact, rating?

The best performance that was realized in these experiments occurred in the full information condition. These data are plotted in Figure 2, along with a line that shows ideal performance. Ideal performance here means that the bounciness ratings would be ratings of elasticity. It is evident in this graph that virtually every mean bounciness rating falls below the ideal elasticity ratings. The rating of the e = 0.50 ball seems to be contaminated by floor effects and so perhaps should not be considered. This leaves exactly one data point that is not below the ideal curve. The systematic departure of the data from the ideal elasticity curve is good evidence that the observers' bounciness ratings are not ratings of elasticity.

In this experiment, as in Todd and Warren's (1982) collision experiment, it pays to consider what the observers are given to look at. The observers watch a simulation of a ball bounce up and down on a computer terminal and are asked to give a bounciness rating to the simulated ball. If one ignores any preconceptions that one might have about the relationship between this experience and physical mappings between kinematic and dynamic variables, then it is clear that a viable observer strategy would be just to base the bounciness ratings on the relative height information. In this context "bounciness" would mean no more than relative height and would have no intrinsic relationship to what physicists call elasticity. Here the observer is regarded as acting simply as a relative height meter. In other words, the observer would be responding only to the kinematics, and a description of performance need only refer to kinematic variables. In this case it would make no sense to compare the ratings with elasticity per se, but one would be conjoined to compare ratings with the distal relative heights. This comparison is also shown in Figure 2.

The relative height observer clearly fits the data better than an ideal elasticity observer. In particular, the data do not show a systematic bias away from the relative height curve. If one removes the two end-point ratings as possibly being contaminated by ceiling and floor effects, the relative height fit is significantly better, $F(7, 7) = 4.55$, $p < .032$. If the entire data set is retained, the fit is still sufficiently improved to be taken seriously, $F(9, 9) = 1.98$, $p < .16$. It can be seen that the high correlation between the data and the ideal elasticity observer is due to the confound that elasticity is the square root of the relative height. The only conclusion that may be drawn from these studies is that observers are quite accurate in their appraisal of relative heights. There is no evidence that any dynamical invariant is recovered, and it is only a fortuity that relative height was assessed in an experiment designed to evaluate perception of elasticity.

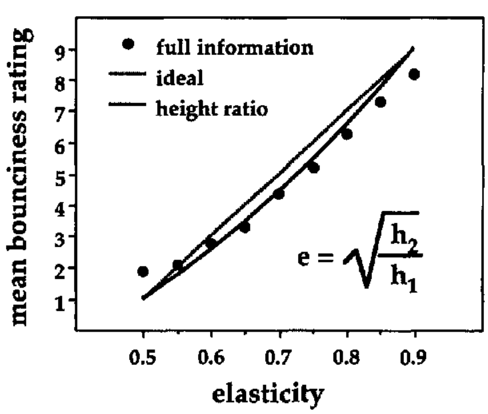

Figure 2. Comparison of bounciness rating data (Warren, Kim, & Husney, 1987) with two models of what is being judged. (The straight line shows an ideal observer who judges distal elasticity. The curved line shows an ideal observer who simply judges the ratio of maximum heights on successive bounces.)

This experiment does successfully demonstrate that not all perceptual quantities can be easily formed into ratios. This, in itself, is quite interesting and is an intriguing phenomenon for psychological investigation. The inability of observers to form ratios of velocities just prior and subsequent to impact may reflect limitations on the time for processing. In the velocity condition, the ball was visible for only 252 to 420 ms depending on the elasticity and starting height. This may not be enough time for representations of velocity to be formed that could serve as a basis for a judgment of ratio. The correlation between velocity ratio and estimated mass ratio reported by Gilden and Proffitt (1989) may have been afforded by the relatively long looking times given to subjects; the postcollision epoch was visible for at least 1 s. The success in estimating maximum height ratios may also in part be due to the fact that the velocity of a bouncing ball is zero at maximum height, and so observers were able to view the balls during this epoch for 1,860 to 3,210 ms.

There may be more fundamental reasons for the inability of observers to integrate durations into a ratio. Schmuckler and Gilden (1989) conducted a series of experiments designed to assess the perceptual domains that allowed sequences of discrete stimuli to be integrated into a contour. In audition it was shown that observers could discriminate the power spectrum of fractal noise sequences when the noises were encoded in tone pitch or tone loudness. Similar results were obtained in vision, where it was shown that equivalent discriminations could be made in a variety of encodings—rectangle heights, rectangle widths, motion of a line, and brightness (Gilden & Schmuckler, 1989). Of all the encodings studied, discrimination was poor only when the noise sequences were encoded in tone duration. Duration in time apparently has the peculiar property that it does not permit organization into a contour. A sequence of durations does not cohere into an identifiable unit that can serve as the basis of discrimination from other units that differ in terms of fluctuation statistics. It may be that the formation of ratios from adjacent stimuli is related to organization into a contour. If so, then the absence of contour formation in our discrimination experiments may be reflecting the same underlying process that rendered the observers in the studies of Warren et al. (1987) unable to extract the higher order ratios from successive bounce durations.

The Visual Perception of Lifted Weight

The extent to which observers can reliably estimate the weight of an object lifted by another person has been investigated in a number of studies (Bingham, 1987; Runeson & Frykholm, 1981, 1983). Bingham (1987) has substantially improved the formulation of the KSD principle by attempting to correlate specific motion functions and weight estimates. In analyzing these experiments, I will emphasize two separate issues. First, it is important to clarify the extent to which people can, in fact, make weight estimates. The existence of this ability is not critical for the KSD principle, but theories of dynamical impressions are interesting only to the extent that people have them. Second, it is necessary to evaluate the nature of the information that people seem to be using in arriving at these impressions. This evaluation is more central to KSD because it supposes that impressions of weight are uniquely derived from the physical organization of lifting motions (to the extent that the mapping between kinematics and dynamics is unique). A problem that is unavoidable here is that the dynamics of human limb movement are not well understood, and consequently the precise functional relationships between kinematic and dynamic variables have not been worked out. With this caveat, it will still be possible to show that heuristic-based analyses are of importance in the impression of lifted weight and that the observers' impressions are related to a small set of simple motion features that do not, in themselves, specify distal weight.

The original data sets on the perception of lifted weight were generated by Runeson and Frykholm (1981). In a first study, visual estimates were made from observing actors lift a series of weights. In a second study, both haptic (actual lifts by observers) and visual estimates were made. The data presented by Runeson and Frykholm (1981) result in two separate interpretations based on whether one averages over subjects or not. In the first study, the average slope of the least squares best fit line between estimated and distal weight was 0.99 for the female actor and 0.75 for the male actor. The slopes, to the extent that they are near unity, suggest that the impressions people form on the basis of visual experience are fairly accurate. There were, however, large individual differences in the slopes. The slope ranges were 0.49 to 1.53 for the female actor and 0.28 to 1.23 for the male actor. Similar results were obtained in a second study in which subjects were divided into pairs; one person made haptic judgments while the partner made visual judgments of the same lift. In this study, the mean slopes were 1.00 and 1.20 in the visual and haptic modes, respectively. Here the range of slopes was again reported to be large; the haptic slope range was 0.87 to 1.68, whereas the visual slope range was 0.56 to 1.33.

Individual differences are not generally problematic in visual psychophysics, but here they are troublesome. The KSD principle is presumably about individuals and the basis for their competence in recovering dynamical invariants. Basic perceptual abilities do not apply to groups; they apply to individuals. If slope ranges of this magnitude had been found in, say, reaching studies, one would suspect that a special handicapped population had been inadvertently surveyed. The fact that gross overestimates by one person are balanced by gross underestimates by another in the mean does not lead to the confident conclusion that people are good at making weight judgments. It suggests, rather, that the generally poor abilities are distributed about the ideal observer.

In these studies a standard weight was specified and made known to the observers. This weight was used to provide calibration of the estimates, presumably to anchor the midrange. It is, in fact, unlikely that absolute estimates would be accurate, although this is an empirical issue. In this methodology the numerical values of the estimated weights are based in terms of haptic or visual information on distance from the standard. The scale properties of such distances are not clarified by this experiment and are not well understood. It is possible that the large variations in slope are due in part to the scaling of weight judgment and to the fact that it is a weight judgment that is made.

The issue of judgment type and scaling was addressed by Bingham (1987), who gave observers the opportunity to judge not only weight, but also the percentage of maximum effort—both of the actor and of what the observers took to be their own abilities. Various scaling conditions were also included: no information about scale, a lift with known standard weight, and a third condition that gave, in addition to a standard weight, the value of the maximum weight liftable by the actor. These experiments differed critically from those conducted by Runeson and Frykholm (1981) by requiring judgments to be made on the basis of one-arm curls (the weight is raised with the palm up by contracting the biceps and closing the angle at the elbow). In the experiments conducted by Runeson and Frykholm (1981), judgments were made on the basis of a complex series of joint motions as an actor picked up a box, set it on a table, and then put it down again.

In a first experiment, the scaling manipulations did not greatly influence the structure of the response curves in the various judgment conditions. Furthermore, there was not much variation in the shapes of the response curves between judgment types. A general inability to discriminate the light and medium weights rendered mean weight estimates as nonlinear functions of lifted weight and were therefore not terribly accurate. Bingham (1987) suggested that the accuracy was reasonable given the poorness of the viewing conditions; the actor's motion was specified only by reflective tape at the major joints, the head, and on the weight.

In this experiment there was additional kinematic information that went beyond the arm motion. First, all weights were lifted three times per event except the heaviest, which might only be lifted twice because of fatigue. This variable specifically introduces kinematic information not of the type envisaged by KSD. If an actor lifts a weight three times per event in the majority of events but lifts the weight only twice once in a while, then counting becomes a viable strategy. Counting is, of course, completely unrelated to the specific motion pattern of a one-arm curl. Second, shoulder motions are more pronounced on heavier lifts, and this allows converging evidence to accumulate about weight heaviness that might be used heuristically in terms of cues; shoulder motion may be treated as a categorical variable rather than as a continuous variable that maps into the dynamics, noting only whether the shoulder moved without reference to the amount of motion. That is, shoulder motion may serve as a clue about the lifted weight. KSD does not traffic in clues, but in continuous mappings.

In a second experiment, Bingham (1987) showed displays that did not have these additional information sources and were further constrained by having the actors wear arm braces to minimize wrist motion. Observers in this experiment were highly inaccurate in their weight estimates, even when a standard weight was provided. The mean estimates were not even monotonically related to distal lifted weight. Even with standard given, the proportion of variance in the estimates accounted for by the actual values of the lifted weights was less than .21. Apparently, there was useful information in the shoulder and wrist motions, and in watching actors strain with weights they could barely lift. It must be stressed that these additional sources of kinematic variation are not compatible with KSD if they are being used heuristically.

The nonlinearity of judged weight, indeed the nonmonotonicity that is clearly evident in the second experiment, is a potential problem for the KSD principle. Bingham (1987) was sensitive to this problem and attempted to reconcile KSD with the data by claiming that there may be important nonlinearities in the mapping between the kinematics and the dynamical quantity of lifted weight. In particular, if the mapping is not one to one or many to 1, then different weights might generate similar kinematic lifting patterns. Under these circumstances, KSD would not assert that recovery of the dynamics is possible. In lieu of a detailed description of the mapping in question, one must resort to analysis of Bingham's own data to determine whether nonlinearities are really the issue, or whether KSD is more fundamentally flawed.

In a final experiment, Bingham (1987) generated phase plane portraits of the motions of the hand during a one-arm curl. These portraits plot instantaneous angular velocity versus angular position as a function of time. Bingham analyzed various functionals defined on the portraits in an attempt to correlate specific motion features with the percentage of expended effort judgments derived from Experiment 2 (although the lifters who provided this data set were not the same as those who served as actors in this experiment). It was found that three measures correlated highly with percentage of effort judgments ($r \geq .90$ for one lifter): lift duration, peak velocity during lift, and average velocity of lift. In particular, peak velocity as a function of lifted weight clearly showed the same nonmonotonic structure as the estimates of lifted weight and percentage of maximum effort.

Bingham's (1987) analysis of the correlation of kinematic variables with judged weight is highly reminiscent of the analysis of the bounciness ratings from Warren et al. (1987) given here. In the previous section I argued that the simplest account of the ratings was that observers were just rating height ratio. The same argument applies here as well. The demonstrated correlations between certain salient kinematic variables and judged weight constitute ample evidence that observers are simply acting as meters for these kinematic variables under the reduced conditions of Experiment 2. Moreover, the observers are really quite good at rating these kinematic variables, as the high correlations attest. What the observers are not good at is estimating weight. The judgment structure is much clearer here because lifted weight is not confounded with the individual kinematic variables, whereas elasticity is completely confounded with the ratio of maximum heights. Although it is true that nonunique mappings could account for poor recovery of the dynamical invariant of lifted weight, these data seem to be indicating instead that observers can be very sensitive to kinematics without having a clue about the underlying dynamics.

In order for the perceptual restriction to nonunique mappings to be established, it must be shown that no combination of kinematic variables leads to a functional that is monotonically related to lifted weight. Bingham's method of considering one variable at a time is not sufficient to establish the argument. Different kinematic variables may interactively contribute to a physical mapping that, as an ensemble of information, is one to one with lifted weight. In a collision, for example, the scalar quantities of speed and direction must be combined into a vector for there to be one-to-one mapping into mass ratio. The possibility of different kinematic variables acting together to specify an invariant raises the difficult question of how observers would combine these variables in acts of judgment. As the collision experiments demonstrate, it cannot be assumed that observers can competently parse the event into the relevant variables. Nor can it be assumed that observers will combine different variables into a functional description that bears any resemblance to the distal mapping.

What Are the Origins of Dynamical Impressions?

The basic premise of KSD, that lawful mappings in the physical world are used by perception in constructing dynamical awareness, has been shown to be either unsupported or contradicted by the data in precisely the domains where experimental confirmation had been sought. These experiments have not, however, served a purely negative purpose. Although they fail to substantiate a particular framework for perceptual organization–KSD, they do suggest alternative models of information acquisition. In this section I formalize what has been learned so far in order to lay the groundwork for constructing alternative models. These models will ask questions different from those asked by KSD and will accent the decision-theoretic aspects of the processes by which dynamical impressions are created. The essence of my argument is that kinematic information has no special priority in perception and that the decisions that one makes about dynamics are rooted within the same processes that lead to decisions in the general arena of human thought.

Formalization of Kinematic Organization

The phenomena considered here are the manifest impressions of dynamical quantities that attend motion events. When objects or people move, one sees more than the displacements, rotations, and accelerations that constitute the pattern in the optic array. This kinematic information is organized, and the experiments that have been analyzed here provide a rich source of observations on the nature of this organization. The following provides a basis for understanding the sorts of representations that people derive from motion events.

The kinematics of a motion event is constituted by the motion of a vector **X** in a phase space that is labeled by position and velocity. **X** can be written in general for any system unambiguously and generates the path that traces the event history. Such a vector has already been illustrated in Bingham's (1987) analysis of arm motion in a lifting action. For many events, **X** is an object of high dimensionality. If one considers the lifts observed in Runeson and Frykholm's (1981) studies, then keeping track of n joints requires a phase space of dimension $2n$. In some cases **X** generates a path in phase space that is quite simple and easily analyzed. A pendulum, for example, generates an ellipse in the space with coordinates (position, velocity). As the pendulum bob repeats its path in physical space (the space of positions that we live in), the orbit in phase space perfectly retraces itself. A pendulum that is damped by friction generates a spiraling motion toward the origin (position = 0, velocity = 0).

In any theory of the origin of dynamical impressions, X and its derivatives constitute the environmental data that provide its support.

In the theory of classical mechanics, there is a class of functions defined on X that are used in both analytical and computational studies of motion. These functions are constant in time, are conserved quantities, and are referred to as integrals of the motion (Binney & Tremaine, 1987). Some of these integrals are easily derived. For example, in any static potential $\Phi(x)$, the energy

$$E(x, v) = 1/2\ v^2 + \Phi$$

is an integral of the motion. If a potential has the further property of being axisymmetric about an axis, then the angular momentum about that axis is also an integral. In the limiting case where the potential has spherical symmetry, the three components of the angular momentum vector $\mathbf{L} = \mathbf{r} \mathrm{x} \mathbf{v}$ (x here denotes a cross product) constitute three integrals of the motion.

The integrals of motion have the important theoretical property of confining the trajectory of X to a subset of lower dimensionality than the phase space. Consider the motion of a particle in some force field. A single particle has three degrees of freedom in position and three in velocity. Consequently, the phase space for this particle is six-dimensional because six coordinates are needed to specify its state at any moment of time. Each integral of motion provides an equation of constraint relating positions and velocities to some constant, and thus reduces the dimension of the set that the particle can, in fact, explore by one. (Technically, there may be integrals of motion that have the property of being constant in time without confining the motion to a lower dimensional subset. These integrals have little value in dynamical theory.) The practical significance of integrals of motion is that they reduce the degrees of freedom available to a system by isolating the orbits; the orbits in phase space are constrained to lie on surfaces that have a constant value, say, of energy or angular momentum.

Isolating integrals are true dynamical invariants, although they have not been identified by KSD or related principles as being of psychological importance. In some cases these integrals contain terms such as potential energies that are not part of the optic array and so may be thought to violate the premise of kinematic specification. However, a potential energy may be inferred from optical structure sampled over time. Thus, an observation of harmonic oscillatory motion might lead to an inference of the existence of a harmonic oscillator potential. Clearly, a machine could be programmed to evaluate the potential energy of an oscillator by simply registering the frequency and amplitude of the sinusoidal time dependence of the particle position. In this case, should one regard the energy integral as being specified by the optic array? Similar analyses would permit computations of angular momentum integrals on the basis of constancy of the direction and magnitude of the cross product between position and velocity.

The dynamical invariants that have been identified by KSD as psychologically pertinent are object properties that are constant over time by virtue of their ontological status as properties per se. The question that KSD addresses is not really how people recover dynamical invariants, but how people recover object properties such as mass ratio and elasticity that are not visible. The physical mappings that are thought to permit the perceptual recovery of object properties are formulated, however, in terms of the isolating integrals. A prime example of this form of recovery is the specification of mass ratio, a relational property of objects, through transformations on the energy and momentum integrals. Similarly, the relational object property of elasticity is defined in terms of ratios that are mutually related by energy conservation (Warren et al., 1987). The separate question of whether the isolating integrals themselves also form perceptual quantities has not been adequately addressed, although Kaiser and Proffitt (1984) have argued that there exist sensitivities to nonconservation of linear momentum.

The perceptual recovery of dynamical invariants requires an analysis of the optic array that is different in character from the mathematical formulation of isolating integrals. Perceptual recovery always requires the assimilation of different pieces of information over time, whereas isolating integrals are formally specified at every moment of time redundantly. For example, in Runeson's (1977) theory of mass ratio specification in a head-on collision, it is necessary for the observer to compare pre- and postcollision epochs. Gilden and Proffitt (1989) have shown that people do, in fact, pay attention to ricochet in both head-on and off-axis collisions, an assessment that patently requires a comparison of velocities at separate moments of time. The specification of elasticity is another example because it is specified only by a perceptual device that can simultaneously take into account pre- and postbounce behavior. A motion analysis that can recover object properties or even integrals of motion will, in general, require that information at different epochs of the event be integrated. It is in this way that recovery of dynamical invariants in perception goes beyond the construction of isolating integrals and becomes a psychologically interesting phenomenon as a problem in perceptual organization.

A physical analysis of the formation of dynamical invariants in perception begins, as in classical theory, with the trajectory X in phase space. Here, however, the trajectory will be regarded as something completed, or as the entire path that is traced out over the entire event. The dynamical invariants, y, shall be regarded as being defined on the completed trajectory. In the cases considered here, these quantities are scalars (i.e., numbers on the real line). This mapping can be written abstractly as

$$\mathbf{y} = F(\mathbf{X}),$$

where y is the dynamical invariant, say mass ratio, lifted weight, or elasticity. Although this class of invariants is defined on the whole phase space trajectory, it is generally sufficient to consider only those values of X defined on certain slices through the phase space. These slices, known as Poincare sections or surfaces of section (see Thompson & Stewart, 1986, for a discussion of the formation of Poincare sections and an illustration), are formed by stroboscopically viewing the motion only when the instantaneous values of X or its time derivatives attain some prespecified value or satisfy some imposed criterion. For example, a Poincare section is formed in the phase space of the bouncing inelastic ball by taking a slice defined by $\{x\text{: velocity} = 0\}$, that is, by stroboscopically imaging the ball just at the times when it bounces and when it reaches maximum height.

To further refine the section, one would distinguish bouncing from reaching maximum height by distinguishing the sign of the velocity on either side of the slice; down–up would be a bounce and up–down would be a moment of maximum height. Similarly, the peak velocities of arm curl define a Poincare section. This section could be made by keeping track of the sign of the velocity derivative.

The function F need not be constructed on a Poincare section. F might consist of integrals over pieces of the orbit that lie between successive passages through a Poincare section. Examples from the studies considered here are the time between impacts of a bouncing ball, the duration of a one-arm curl, and the average velocity of a curl. In the orbit integrals for a one-arm curl, a convenient section would be defined by the maximum opening angle at the elbow.

In the analysis of collisions, the phase space trajectories are particularly simple because the velocities in the precollision and postcollision epochs are constant. Here Poincare sections are not required or useful because the velocities in each epoch are constant, and the critical information in phase space is the discontinuity at the moment of collision. The physical analysis of collisions is restricted to developing the jump conditions at the discontinuity through the conservation laws for momentum and energy.

From an information-theoretic point of view, there is a substantial amount of organization that occurs in the construction of F. Focusing on key moments in an orbit by means of a Poincare section collapses the dimensionality of the set on which the analysis is performed. Instead of requiring knowledge of the positions and velocities over an entire trajectory, one need only consider a sequence of, say, maximum heights or peak velocities. There is also organization implicit in constructing integrals over orbits. The average velocity or duration of a one-arm curl provides a compact summary of what is otherwise a complex motion event. In both the construction of Poincare sections and integrals along orbits, much information is lost. In fact, one could correctly argue that essentially all of the information has been discarded in the sense that the constructed set has measure zero (no volume) in the phase space of the orbit. This, however, is the hallmark of organization and the price that is paid for it. Organization is, in part, a focusing that abstracts the essential ingredients from an event. The phase space trajectory of **X** is not organized; it is a complete list of absolutely everything that happened in the event. Organization begins with culling this list for critical moments and by summing over the list to project specific quantities.

The organization that is implicit in the Poincare section and in the orbit integrals is only the initial step in the specification of a dynamical invariant. The sequence of points in a Poincare section is, after all, just another list. Forming a dynamical invariant in physics or forming a dynamical impression in perception will generally require that something more be done with this reduced set. Further organization acts to reduce the entire event to a single real number, the dynamical invariant. If the event is repetitive, say as in a one-arm curl, then the list may contain nothing more than the iteration of a single value. In this case, that value may provide useful information, and, in fact, Bingham's (1987) observers correlated lifted weight with the single quantity of peak velocity. However, if the event is not repetitive, as in the repeated bouncing of an inelastic ball, then the values on the Poincare section will not be constant, and further organization is indicated.

As an example of organization on a Poincare section, consider the sequence of maximum heights that are attained by an inelastic bouncing ball. Organization in a physical analysis of elasticity requires that points on the section be grouped pairwise in overlapping sets: (h_1, h_2), (h_2, h_3), (h_3, h_4), and so on. These dyads are then mapped into the real numbers through the transformation

$$F(a, b) = a/b,$$

and then the square root is taken. Each dyad maps into the same real number, and it is the constancy of this number that forms the dynamical invariant of elasticity. A similar analysis of elasticity could be given in terms of duration between bounce. Duration is an integral over the orbit and, just as the introduction of a Poincare section, its computation collapses a part of the **X** trajectory into a single number. The dyad grouping on overlapping pairs of durations and the formation of ratios follows as before. Whether a square root of the ratio is taken or not is not material in the construction of the invariant.

Two-body collisions are not analyzed on Poincare sections or through other culling devices because the event is completely constrained by the jump conditions across the motion discontinuity at the point of impact. The kinematic information in the event is already reduced to a minimum—the pre- and postcollision velocities. However, the parsing of a collision event relative to the point of impact is an act of organization that is not trivial. It allows the trajectories to be reduced to four constant vectors. From this point, the organization of these quantities into a mass ratio is formally almost identical to elasticity organization. In the most general collision, which is an off-axis impact, the postcollision velocities are grouped as a dyad (v_1, v_2). This dyad is then mapped into the reals through the transformation

$$F(a, b) = a \cdot \mathbf{u}_y / b \cdot \mathbf{u}_y,$$

where $\mathbf{u}_y$ is unit vector in the direction orthogonal to the collision axis (has length equal to unity) and the dot product has been taken. This particular grouping yields the mass ratio.

In this section it has been shown how a complex orbit in phase space can be organized through successive transformations to yield a dynamical invariant. At each stage of transformation, organization was effected by a narrowing of focus. Phase space trajectories were projected onto Poincare sections, integrated, or split into epochs. This reduction was followed by dyadic separation. A final step in the organization was effected by transforming the dyad into a ratio. The ratio is the dynamical invariant. The examples worked out here generalize to other motion events, although more complex systems may have more complicated functionals. However, the basic transformational stages will have the same form because the organizational problem is ultimately the same—the transformation of an ordered list of positions and velocities into an invariant quantity.

Perceptual Organization of Kinematic Information

The experiments reviewed in the previous sections have given some insight into the way people organize kinematic information. As shall be seen, perceptual organization shares many of the same properties as formal kinematic organization, although perception departs at an early stage from physics. What follows is a summary of what has been learned about the modes of perceptual organization that permit dynamical awareness. In the absence of a theory, a series of questions remains. The intent and the force of these questions is to revive this area of psychological inquiry by recognizing the difference between human protocols and the protocols dictated by physics.

Segmentation. The first, and perhaps the most amazing, observation that derives from the experiments discussed earlier is that people reduce the kinematics in a way that has a startling similarity to the formation of Poincare sections and orbit integrations. This ability cannot be taken for granted. Evidence for the existence of this type of perceptual organization is implied in every experiment that has been analyzed. In Warren et al. (1987), observers stated that they attended to maximum heights, and the rating data for bounciness showed unambiguously that they formed ratios of successive dyads. Observers in collision experiments give mass ratio ratings proportional to ratios of postcollision velocities. Bingham's (1987) observers rated lifted weight in proportion to peak and average velocities as well as to duration of lift. Why would observers naturally resort to these particular forms of information reduction?

The problem for observers judging motion events is to represent the kinematic information in a way that reveals their underlying shape. The notion that an event in time has a shape is informal and only intuitively based, but that does not discount its utility as a point of departure for psychological investigation. The analogies with spatial shape are easily developed, and the phase plane portraits of motion events may be regarded as providing the appropriate spatial analog. A fundamental problem that exists in both spatial and temporal conceptions of shape is the way in which events in the two domains are perceptually segmented. Formal analyses of segmentation that have been developed for spatial vision offer both the tools and the concepts for understanding segmentation in time.

Discontinuity plays an obvious and important role in image segmentation. There are two central issues in understanding how distal discontinuities specify visual boundaries in perception. The first problem is in identifying what properties of an image must be discontinuous in order for a perceptual boundary to arise. Julesz (1975, 1981) has shown, for example, that discontinuities in the second order statistics generally suffice for preattentive boundary identification. The phenomenon of perceptual pop-out has been used generally to determine the basic feature maps that potentially carry boundary information (Triesman & Gelade, 1980; Triesman & Paterson, 1984). A second problem is in characterizing the information that specifies the distal source of the discontinuity, whether it is by occlusion, a reflectance edge, a cast shadow, or some other textural property.

Discontinuity in the temporal domain is intrinsically much simpler than spatial discontinuity. Time is not projected onto a lower dimensional subset, as occurs in the two-dimensional retinal projection of three-dimensional spatial layout. This means that temporal discontinuity cannot arise from degeneracies inherent in a projective transformation (e.g., as in occlusion). More important, the only truly discontinuous transitions that occur in phase space trajectories of natural motions are caused by collisions. Any other instance of discontinuity indicates the presence of cognitive intention or the sudden activation of a force that is not ambient. Thus, discontinuity in time may be used for assessing whether a motion is "natural" or not. If a discontinuity in velocity is noted that is not attended by a collision, then the observer has evidence that the motion is not physically possible without the intervention of an unseen agent.

Spatial segmentation may also occur within the analysis of continuous variation. One of the most profound insights that has been gained from the computational theory of the early visual system (for reviews, see Barrow & Tenenbaum, 1986; Marr, 1982) is that a system that contains simultaneous excitation and inhibition may represent continuous changes in a distal variable as a change in sign. For example, theories of edge extraction begin with a representation of luminance changes in terms of patterns of zero-crossings (Marr, 1982; Witken, 1986) on varying spatial scales. Zero-crossings are computationally robust because they discard information about derivative magnitudes that may be noisy, in favor of changes in sign of the discrete second derivative operator (difference of Gaussians) that are less influenced by noise. Similar arguments have been given for the computational advantage that opponency in color vision affords; discrimination between colors may be mediated by a change of sign of the output of an opponent cell rather than just as a quantitative change in the magnitude of firing rate (see Goldstein, 1989, for a review of this argument).

The importance of sign change has been highlighted in geometric theories of boundary segmentation. A key descriptive quantity in the differential geometry of curves is the curvature at a point. Curvature is calculated in terms of the instantaneous rate at which a tangent line turns as a point moves along the path. The curvature of a surface is similarly defined in terms of a set of tangents that form the basis of the tangent space at a point. Image theorists have used the tangent structure to develop perceptual protocols for boundary segmentation in completed contours (Hoffman & Richards, 1988) as well as in amodal or subjective contours (Shipley & Kellman, 1990). These theories are framed in terms of local maxima or minima of the tangent velocity along a path where the second derivative is zero. The relation between the tangent structure and perception is that people seem to segment continuous boundaries at zero-crossings of the curvature derivative.

The perception of kinematic trajectories may be analyzed using the same techniques from differential geometry that have pervaded image understanding. The only difference is that spatial trajectories are differentiated with respect to time rather than spatial contours with respect to position. The focus here is on velocity—its continuity, its sign, and the sign of its derivatives. Consider the motion events described in the preceding experiments. When a ball bounces and when it reaches maximum height, the velocity changes sign. In particular, at the moment of bounce, the velocity changes sign discontinuously. The point of peak velocity in a one-arm curl is marked by a change in sign of the acceleration. The collision between two objects is marked by a discontinuity in velocity. In all cases it can be seen that there are specific geometric features in the velocity structure at just those points where observers extract information for subsequent event analysis. Often the critical feature is a discontinuity in velocity that physically requires an epoch of sudden acceleration. Although it is true that accelerations are related to forces in motion events, I am not suggesting that people have special sensitivities to the existence of forces. Rather, the sensitivity is presumed to be related to specific features in the velocity history of the event. This perspective allows the impressions of forces as well as the perceptual placements of Poincare sections to be unified by a protocol that analyzes the differential structure of the kinematic trajectory.

There is additional evidence from judgments of what is natural that people are quite sensitive to discontinuities in velocity or changes in its sign, and that they use this information to segment events. In experiments conducted by Proffitt, Kaiser, and Whelan (1990), it was shown that observers had little sensitivity to the correct variation in rotation rate of an object that increases its moment of inertia about the rotation axis (e.g., ice skaters slowing as they bring their arms from vertical to horizontal). Observers rejected as unnatural only those displays in which the rotating object stopped or reversed direction. Pittenger (1990) found, by accidental procedural errors, that observers are extremely sensitive to discontinuities in the velocity of a pendulum. Similarly, Kaiser, Proffitt, and Hecht (1990) found that the trajectory of a cut pendulum bob looked unnatural in just those circumstances when the bob velocity was discontinuous at the moment of cutting.

The criterion that is apparently used in naturalness judgments is that motion events that are perceptually segmented are judged to be unnatural unless there is explicit awareness of a force that could cause the event to split. This heuristic is predicated on the existence of some geometric feature in the velocity history that could lead to segmentation. The two features that have demonstrated importance are velocity discontinuity and change in velocity sign. The naturalness judgment further requires that there be prior notions of the way certain forces are manifested. Examples of such notions are that collisions are attended by discontinuities and that gravity may cause changes of sign in linear velocity. A ball thrown in the air undergoes a change of sign in the velocity at maximum height, but this clearly looks natural because this is the way gravity is known to work. However, gravity does not cause rotating objects to change the sign of their angular velocity, and apparently people can recognize this; it looks unnatural if a rotating object reverses the sign of its velocity.

The claim that naturalness judgments are heuristically based on segmentation protocols and world knowledge is in direct conflict with KSD notions that naturalness can be specified as an inherent property of a kinematic trajectory. An informal proof of this claim is the existence of objects that are regarded as toys because they are natural and yet violate the matching of world knowledge with segmentation protocols. There are two toys that are particularly relevant here. The first is known as a spinning celt. Spinning celts are almost ellipsoidal, but their slight deviation from perfect symmetry causes them to behave rather peculiarly. When spun in one direction, they rotate as expected. When spun in the other direction, they slow down, oscillate back and forth, and then start rotating in the other direction. The other toy is known as the tippy top. A tippy top is formed by truncating a sphere and placing a stem in the missing section. College rings with a smooth stone will also work. When a tippy top is spun, it turns over, the sign of the angular velocity changes, and it spins on its stem. Both of these dynamical puzzles are worth viewing. Tippy tops and spinning celts operate in the way they do because of torques induced by frictional forces. People apparently do not have world knowledge about such interactions, and this leads to amazement when the event segments through a change in the sign of the velocity.

These observations lead to a segmentation criterion; impressions of dynamics are afforded by information obtained at the moments where events are perceptually segmented. Consider now the converse of the segmentation criterion; events that are not segmented by perceptual protocols on the velocity structure will not afford impressions of dynamics. A corollary of the converse is that naturalness judgments on motions that do not segment according to velocity protocols will only be made within wide acceptance ranges. Perhaps the best evidence for the dependency of dynamical impressions on the existence of segmentation features are toys such as tops and gyroscopes. The motion of a precessing top can provide amusement only because the dynamical invariants are not specified by the kinematics. In particular, gravity is specified by precession, and there is sufficient information in the optic array for its presence to be implied (the magnitude of the gravitational acceleration is confounded with the top's mass and a component of the inertia tensor). Yet there are few people who see precessing as a form of falling. The breakdown in the recovery of dynamical invariants is much worse here than in observations of collisions or actors lifting weights. In the latter events, there was always some impression of dynamical quantities, even if it was unrelated to the distal values. Tops, on the contrary, appear to be magical. It is suggested here that the complete incomprehensibility of objects like tops may be related to the fact that the event cannot be segmented. In two senses, the event is too smooth. The precession and rotation motions are smooth monotonic functions of time (nutation can be segmented), and so the event affords no foothold for perceptual processing that could lead to dynamical impressions.

Proffitt and Gilden (1989) suggested that the breakdown of dynamical understanding of such objects as tops was due to the many different variables (mass distribution, rate of spin about axis of symmetry, angle of inclination, etc.) that have to be integrated into a coherent representation of the motion. This point of view is not negated here, and the collision experiments do demonstrate that combining even two kinematic variables (direction and speed) may be difficult. There may be, in addition, other reasons why gyroscopic motion is perceptually impenetrable. The physics of rotational motion requires that cross products be formed. The direction of a cross product is not along an axis that is perceptually specified. For example, precession occurs because of the cross product between the angular momentum vector and gravity. Gravity points downward and is always specified, and the symmetry axis of the body specifies the direction of the rotation. The cross product is orthogonal to the plane formed by these two vectors and so the top precesses "sideways." The inherent invisibility of the direction of the cross product may be the key to why people can find amusement in gyroscopic motions. All three of these accounts are plausible and possibly relevant. The data, however limited, do indicate that segmentation cues must be present for clear impressions of impossibility. Where impressions of dynamical impossibility are not present, it is doubtful that there are clear impressions of the dynamics per se.

The qualitative similarity in the manner in which spatial and temporal information is segmented suggests that these sensitivities are of a general nature and not specifically linked to motion. That motion events occur in time and are governed by physical laws may be quite beside the point. Segmentation appears to be ruled by general principles of organization that are independent of the sensorial modality. That such rules are often compatible with the natural structuring of events may be due to the internalization of natural regularities (Shepard, 1984), the direct perception of useful information (Gibson, 1979), or the automatic and tyrannical application of the Gestalt law of good continuation. Accounting for the ability of people to organize kinematic information into low dimensional subsets or into specific integrals is not accounted for by KSD or any other theory. It is an unsolved problem in perceptual organization.

Dyad formation and ratio comparison. A second observation about the organization of motion events is that people, under some circumstances, form dyads on restricted sets of kinematic quantities and effect the computation of ratios. This ability was demonstrated in the elasticity studies of Warren et al. (1987) and in the collision studies of Todd and Warren (1982) and Gilden and Proffitt (1989). The utility of these transformations is that they permit information to be compared. Dynamic impressions are based on these comparisons, and the extent to which people have awareness of dynamics is intimately related to their abilities to compare information within a dimension (variable type—velocity, angle, height, etc.) and across dimensions.

Definition of the perceptual dimensions that are susceptible to internal comparison is an empirical issue that can only be addressed by assessments of how the variables in each case are scaled. The abilities that observers have in forming velocity and height ratios, but not duration ratios, are not predicted by any theory. There is also little understanding of the perceptual resort to dyadic comparisons within a variable type. It may be that more complicated comparisons are attempted and have not been experimentally resolved, or that there are perceptual limitations and processing constraints that make higher order comparisons intractable. In KSD the dyadic grouping and ratio computation are taken for granted. Here they are regarded as a source of puzzlement and psychological inquiry.

A problem not recognized by KSD, but one that is potent for human observers, is how information from different kinematic dimensions is to be compared. This problem is realized most vividly when comparisons on different dimensions lead to conflicting heuristic assessments. Recall that in both Todd and Warren's (1982) and Gilden and Proffitt's (1989) collision experiments, when the ricocheting ball had a much smaller exit speed, observers were completely baffled as to which ball was heavier. The origin of this muddle was traced to a decision procedure that considered the exit angles and exit speed ratio separately. Under these circumstances, observers might attempt some sort of trade-off between speed and angle information. However, the bimodal magnitude estimates found by Gilden and Proffitt (1989) imply that people have no protocol for comparing speed and angle information in the assessment of mass ratio. The inability to effect a trade-off may be due to the way the different sources of information are represented. The angle information may be categorical (Did the incoming ball ricochet or not?), whereas the speeds seem to be represented as a continuous variable, possibly on a ratio scale (see Luce & Krumhansl, 1988, for a discussion of scale type). It is not clear how categorical and continuous variables could be traded off to achieve a compromised estimate of mass ratio. In fact, no subjects in the conflict condition estimated the mass ratio near unity. The bimodal distribution of mass ratio estimates in the condition of heuristic conflict illustrated a particular type of decision—just ignore one dimension.

The observation that people are ineffective in combining information from perceptually separable dimensions is not confined to the perception of motion. Shepard (1964), in a simple but elegant experiment on perceived similarity, showed that judgments in this domain tended to be based on only one variable (in the experiment referred to, the variables were position of a tick mark and size of an enclosing circle). These judgments were not optimal in precisely the same sense as developed here; there was no attempt to take both variables into account. A decision protocol that takes only one variable into consideration must tolerate arbitrarily large disagreements in the ignored dimension. The implied dominance metric also produces judgments that are bimodally distributed with the attendant large degree of intersubject variability.

There is evidence from a number of domains that the decision procedure used to evaluate mass ratio does not generalize. A good example is the development of understanding of the two-arm balance (Siegler, 1978). Naive appreciations of the two-arm balance are dominated by two heuristics: The side with the most mass goes down, and the side with the weights further from the fulcrum goes down. The mass heuristic develops first and the application of the distance heuristic follows a set of stages. The final stage, realized in only about 50% of college-aged adults (Proffitt & Gilden, 1989), requires that mass and distance be traded off (in this case, multiplicatively to form a torque). An observer who can combine mass and distance in a judgment of which arm will go down is able to solve the conflict problem where the heavier weight is closer to the fulcrum. The reason that many observers can combine mass and distance information competently may be the convergence of the scales on which these variables are psychologically measured. Both mass (represented in these experiments as size of weight) and distance generate psychological magnitudes that are power laws of the distal stimulus (Luce & Krumhansl, 1988). At present, there is no theory that describes those domains that permit information integration in the analysis and recovery of dynamical quantities.

Conclusion

The experimental evidence for the KSD principle, that dynamical understandings are specified by kinematic information through unique physical mappings between kinematics and dynamics, has been evaluated in three different experimental domains. It has been shown that the underlying dynamics is not recovered from the kinematics, and in each case it has been demonstrated that dynamical impressions are related to a set of simple features or ratios of specific kinematic quantities. These ratios and features appear to be used heuristically and without any particular appreciation for their relationship to the true dynamical invariants.

A formal analysis of the specification of dynamical invariants in terms of transformations on the kinematic information in phase space has been given. It has been argued that people manage to isolate critical episodes in motion events by exploiting segmentation protocols that highlight velocity discontinuities and changes in sign of low order time derivatives of the physical trajectory. These protocols are not limited to motion analysis and have isomorphisms in the segmentation of spatial contour. It has been demonstrated that people sometimes are able to form dyadic functions on Poincare-like sections and compute ratios, although the circumstances in which this ability is manifested await clarification.

Finally, it has been suggested that the origin of dynamical impressions has its foundation in decision theory. The issue of comparison of information within and across dimensions of information is not intrinsic to event analysis. It is a general problem in decision-making and choice behavior (Roberts, 1979; Tversky, 1972). If the problem of the recovery of dynamical impressions is posed in this way, then an entirely different focus emerges. Instead of supposing that smart perceptual devices accomplish the extractions for them (Runeson, 1977), people are left with the complexity that attends human decision making. The fact that this is decision making under certainty—that there is a complete physical model—does not alter the nature of the psychological problem. The questions that are raised in this context bear little resemblance to those that arise in KSD or in equivalent theories that postulate that people have special access or sensitivities to physical relationships. At a minimum, one wants to know the circumstances under which people are prepared to make judgments on more than one variable type. In those circumstances where conjoint models are attempted, one wants to know whether they satisfy the axioms for transitivity and additivity. Is there a general structure that people use in comparing different dimensions of information? Are psychological models of dynamics intrinsically separable; that is, what are the judgment structures in domains where the distal mappings among variables do not separate into individual functions defined on one variable? In this approach, theoretical investigations into the origins of impressions of dynamics are not differentiated in their structure from theories of impressions of what is sexy, what is virtue, or what is a good buy.

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