

Are conceptions of motion based on a naive theory or on prototypes?*

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Abstract

Individuals untutored in physics sometimes answer questions about motion in ways that are internally consistent but highly incompatible with accepted physical theory; this might mean that they have formulated personal "naive" theories of motion from which they deduce answers to problems. However, interviews with subjects solving motion problems showed that problem solution is subjectively experienced as the result of a mental enactment of the situation, rather than as a deduction from a theory. Variations in the enactment (produced by variations in the portrayal of the problem situation) frequently led to changes in response, indicating that enactment is functionally (as well as subjectively) the source of responses. The source of the enactment itself appeared to be a number of mutually inconsistent, relatively specific prototypes which capture typical aspects of motion, rather than a theory composed of general principles. Subjects solved problems about unfamiliar situations for which personal experience was insufficient by developing analogies to more familiar situations. Although individuals appear to develop knowledge which qualifies as a "theory" of motion, the results do not support the view that these theories are composed of general principles like those of scientific theories.

McCloskey (1983) and others (Caramazza, McCloskey, & Green, 1981; Champagne, Klopfer, & Anderson, 1980; Clement, 1982; McCloskey, Caramazza, & Green, 1980) have discovered that when untutored informants

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are asked questions concerning the physical world, they sometimes give responses that violate the principles of Newtonian physics and seem at odds with any conceivable observation. For instance, McCloskey (1983) asked subjects to respond to the sling problem: The informant is asked to think about a metal ball being swung round at the end of a string, and asked to draw the path the ball will follow if the string breaks when the ball reaches a specified point.

While some subjects give the Newtonian response—a straight path tangent to the ball's orbit at the point of release—others draw a curved path, or a straight path that is clearly not tangent to the orbit. From the pattern of results on this and other questions concerning motion, McCloskey concluded that many individuals develop a naive theory of motion which guides subjects' responses to questions about motion, sometimes generating responses that are in striking conflict with standard physical theory.

It has become common to claim that individuals possess indigenous theories for a great variety of conceptual domains (Carey, 1985; Chomsky, 1957; Gelman & Gallistel, 1978; Karmiloff-Smith & Inhelder, 1974; McCloskey, 1983). Our concern in this paper is with the underlying nature and internal structure of naive theories in general, but especially with reference to naive physical theories.

Although the precise form of naive theories is usually not at issue and so is often not explicitly discussed, claims that individuals possess naive theories in various knowledge domains implicitly draw an analogy to scientific theories. Traditionally a scientific theory is taken to be a set of explanatory principles, axioms, or laws which state abstract and very general relationships among a specified set of variables. The basic metaphor of this view is that scientific theories are composed of a language-like set of propositions. This view has a long history; the conviction that knowledge, especially scientific knowledge, must be composed of a set of rules or principles can be traced as far back as Plato (Dreyfus & Dreyfus, 1986). The theory position can be contrasted to the position that the growth of knowledge consists merely of increasing expertise—learning more and more facts about the world, leading to an expanding repertoire of strategies and concepts to deploy in dealing with it (e.g., Chi & Glaser, 1980; Flavell, 1982). Thus the theory position establishes an important polarity between empirical knowledge and theoretical knowledge.

Is this traditional view of a theory what cognitive researchers have in mind when they attribute theories to individuals? Although the term theory sometimes appears to be used merely as a contrast with observation (as when Karmiloff-Smith & Inhelder, 1974, contrast children's physical theories with "mere observation of immediate empirical reality" [p. 208]), the contrast is

itself a significant aspect of the theory position. Furthermore, other authors are more explicit in considering indigenous theories to consist of laws (Carey, 1985) or principles (Gelman & Gallistel, 1978). With respect to naive physical theories, this appears to be the view McCloskey and his colleagues accept (see McCloskey, 1983, p. 299).

However, there are other ways in which subjects might generate answers to questions about physical motion even in the absence of relevant principles, and without accepting the dichotomy of empirical and theoretical knowledge. Yates (1985) has proposed that conscious experience has the form of a model of the world, composed of a set of discrete prototype objects, events, and situations (Rosch, 1973, 1977), in which imaginary events can be simulated, or enacted. The model of the world thereby allows complex imaginary events to be experienced as if they actually had occurred, an extension of Shepard's finding that subjects can experience the rotation of mental objects (see Shepard & Cooper, 1982, for a review). Just as subjects can answer questions concerning form by enacting the rotation of a random form, they might answer a question about motion, such as the motion of a sling, by drawing on past experience (in the form of prototype events and objects) to create an enactment of the event implied by the question. Enactment is the literal experiencing of an event without external stimulus support, made possible by the internal model of the world (de Kleer & Brown, 1983, have called this experience envisionment, simulation, or running).

As opposed to a language-like set of general propositions, this view relies on the basic metaphor of what is often called, in everyday parlance, an image (with the understanding that much more than visual information is included, and that a mental object is not anything like an unstructured photograph). After mentally experiencing the event described by a motion problem, subjects respond by merely copying on paper what "happened" in the enactment. Responses are thus ultimately based on relatively concrete prototypes which specify that which is typical, rather than on general principles which apply universally.

A sketch of an enactment episode for a physical motion problem, such as the sling, is as follows (see Yates, 1985, for general properties of enactment): Out of the available set of event prototypes, that prototype which most successfully accounts for the problem description and is most readily modified to account for the atypical, idiosyncratic aspects of the event becomes the *conception* (loosely, a miniature, special purpose theory) of the event. This instantiated prototype possesses an internal structure consisting of components interrelated in specified ways that allow the subject to "run through" or enact the conception, experience the motion in question, and respond accordingly. Furthermore, just as one can use attention to focus on one or

another aspect of an external event, the same attention operations can be applied to instantiated prototypes to change the relationships among various elements of the internal structure, thereby changing the enactment.

Instances occur where these steps do not lead to a successful enactment which specifies a path for the queried situation. Subjects may then engage in structure mapping (a term used similarly by Gentner & Gentner, 1983; also see Lakoff & Johnson, 1980; Kuhn, 1970, postscript), in which a prototype with some structural similarities (determined by the internal structures of the respective conceptions) to the described event is used to achieve a metaphorical conception of the event. For instance, for the sling problem described above, one might generate a response by thinking about the effects one has experienced in jumping off a merry-go-round. The content of the prototype employed is clearly inappropriate as a literal account of the described event, but it possesses some of the appropriate internal structure.

In addition to being the basis for imagination, the model of the world is what is experienced in witnessing real external events, and it is the source of real external acts (Yates, 1985). Collapsing the empirical/theoretical dichotomy in this way leads to two important points. First, the unity of imagination and action leads us to expect that enactment may sometimes spill over into actions performed *in vacuo* during enactment.

Second, the unity of perception and imagery carries the important implication that in witnessing any event, individuals actually observe their own conceptions rather than the physical event itself (Yates, 1985). This accounts for McCloskey and Kohl's (1983) finding that subjects give the same responses when observing and interacting with objects as when responding to hypothetical problems.

Thus even though the prototype approach explains solutions to motion problems by referring to past observations or experiences, this is not an empiricist account of motion knowledge. Because observations are actually conceptions, the prototype approach does not predict that observations must be veridical, nor can one draw a distinction between anticipations of motion based on simple recall of some physical event empirically observed in the past versus those anticipations generated by theoretical knowledge (Kaiser, Jonides, & Alexander, 1986). Because observations are not necessarily veridical, predictions of motion based on observations may deviate markedly from the true state of affairs. In allowing physically incorrect predictions of motion, the prototype approach is more similar to the theory approach than to a purely empiricist approach.

These brief outlines of the theory and prototype positions allow some general distinctions to be drawn between them. The basic distinctions can be summarized by examining in each the status of empirical observation, the

generality of actual and ideal accounts of the world, the limitations placed on memory, the role of conceptual typicality, and the ultimate nature of reality.

Empirical observation

As previously mentioned, the theory position distinguishes between a theory or principle, which reveals the underlying nature of the world, and an observation, which when done properly is a representation – that is, a mirroring, or copy of the world. This view thus retains one of the central distinctions of a realist/objectivist approach to knowledge. While it is often said that theory influences observation (and it goes without saying in this view that observation influences theory), the two are retained as separate categories.

In contrast, the prototype approach does not distinguish between theory and observation. The same entities serve both purposes. Those who maintain that theory (or cognition) influences observation without abandoning this contrast altogether (Hanson, 1958; Kuhn, 1970; Neisser, 1967) are in this view retaining an unwarranted distinction. Once the waters are thus muddied, the distinction becomes unparsimonious.

Generality

If the theory position is not to be vacuous it must be assumed that indigenous theories are analogous to scientific theories. As mentioned earlier, the view of scientific theories tacitly adopted by those proposing naive theories appears to be the traditional view: Theories are composed of principles which are in turn taken to be quasi-linguistic quasi-logical propositions. The propositions are usually conceived to be quite general and situation-independent (i.e., not expressed in terms of specific situations or even classes of situations).

When a naive principle is not completely general, this state of affairs is tacitly viewed as a deficiency or as an early stage of development. Thus Caramazza et al. (1981) remark on the apparently deficient character, relative to Newtonian laws, of the principles of motion they discovered in subjects. Gelman and Gallistel (1978) state the numerical concepts acquired by children in the most general terms, even though they may be applicable only in situations with three or fewer objects. Carey (1985) proposes that the course of conceptual development involves restructuring relatively narrow and isolated concepts into more general theories that more properly mirror underlying domains of reality. The course of development found in Piaget's system is likewise from concrete situation-specific structures to increasingly mobile and general structures.

Consequently general principles are the ideal on which all others are modeled. Even when principles appear limited in their application, these limitations are not often expressed by casting the regularities to be accounted for in terms of actions in situations, but by postulating a general principle that is then delimited by a *ceteris paribus* (CP) clause (as general Newtonian principles must be tempered by qualifications concerning air resistance, friction or non-point masses).

Setting up general principles as the ideal, as the theory position does, is justifiable given several other assumptions of that view. That naive theoretical principles are valuable or adaptive to the extent that they are general is entailed in part by the contrast between theory and experience in this view. To the extent that a theory is situation-specific, it merely duplicates observations.

Whereas theories are presumably composed of language-like principles, mental objects are strictly speaking not composed of anything. They are just what they are. However, each mental object does possess an internal structure (parts in relationship) that in principle can be described in words even though neither the structure nor its content is language-like.

In the prototype view the issue of duplication of observations by situation-specific conceptions does not arise, because this approach allows no distinction between theory and observation. Situation-specific mental objects cannot duplicate observations – they *are* observations.

Thus unlike general principles mental objects are by definition situation- or object-specific. If two situations are subjectively different, then they must be two distinguishable mental objects. However, mental objects can be general in a different sense. By deeming irrelevant many aspects of the world, one can make situations or objects identical that are in principle distinguishable. When one employs the term vehicle, one regards many distinguishable aspects of cars, trucks, bicycles, and so forth as irrelevant.

The situation-specificity of mental objects prohibits them from possessing another valued property of general principles, their applicability to unanticipated circumstances. Unlike situation-specific knowledge, principles allow the assimilation of an infinite number of novel cases never before experienced. Ideally, general principles can assimilate all possible relevant cases. In contrast, the prototype position allows only some novel instances to be assimilated, using structure mapping.

Memory

Implicit in the theory position's ideal of a few very general principles that are quite distinct from observations is parsimony with respect to memory. In

order to conserve memory, principles should not merely duplicate observations, and the more general they are the more cases each principle can cover. Hence the need for fewer principles to be stored in memory.

With mental objects there is no attempt to be parsimonious with memory storage. The assumption that memory is limited appears to be based on a faulty analogy to mechanical, electrical and electronic memory devices. On the contrary, evidence using incidental learning paradigms indicates that memory for conscious experiences is essentially unlimited (e.g., Morris, Bransford, & Franks, 1977).

Ultimate reality

Perhaps the most important reason within the theory position for making general principles the ideal is that whereas observations mirror the real world, a theory mirrors a deeper reality—an underlying reality that is considered more real or more basic than what is seen or experienced. Theories inform us about the basic nature of the world, and the theories containing the “deepest” generalizations have priority over lesser theories because they are the most revealing of reality. This point leads to a hierarchical arrangement of more and more general theories (the hierarchy may be historical, developmental, or merely conceptual). For example, the principles of Newtonian physics are often considered to be more general than those of pre-Newtonian physics but less general than those of contemporary physics. The Newtonian model is therefore considered a less faithful rendering of physical reality than theories incorporating relativity or quantum mechanics.

In the prototype approach reality is pluralistic rather than hierarchical. Psychologically, conscious experience is the ultimate reality, and any aspect of the world can be accounted for in awareness by an infinite variety of mental objects, depending on one's values and purposes. No one mental object has epistemological priority. In this view the Newtonian concept of inertia is distinct from, but not deeper than or superior to, the pre-Newtonian concept of impetus. In short, all realities are equally deep, although given a particular set of purposes or values, one reality may be preferable to another.

Typicality

Some mental objects are considered normal, frequent, and to be expected, often by virtue of one's culture and its values rather than because of environmental frequency. These mental objects, called prototypes, assume a leading role in guiding expectations and formulating predictions concerning the world. This characteristic is not explicitly incorporated in extant versions of the theory approach.

Having distinguished in general between the theory and prototype approaches, we turn to physical beliefs in particular, where the theory position and the prototype position yield maximum contrast concerning (a) the number and generality of elements comprising knowledge of motion, (b) the presence of CP restrictions which provide for special cases and exceptions, (c) the manner in which individuals generate a response to novel questions about motion, and (d) the role of enactment. The theory approach posits a small number (perhaps dozens) of situation-free language-like principles that parsimoniously account for observations. These principles are completely general except for CP restrictions; therefore a person's views concerning motion are expected to be internally consistent over a wide domain of situations, but should be tempered by information relevant to important CP restrictions. The great generality of the principles accounts for the ability to answer novel questions concerning motion; analogies or mappings to more familiar situations are given no special place in this system. The theory approach is completely neutral concerning the possible role of enactment.

In contrast, the prototype approach posits large numbers (perhaps thousands) of situation-specific image-like prototype events that provide a conceptual account of physical events. The conception consists of the prototype's internal structure, which specifies the relevant dimensions of the physical event.¹ In this approach knowledge is not systematic, and a person's views concerning motion are not necessarily consistent across even closely related situations. Because every situation is "exceptional" in this approach, situations need not be analyzed for the presence or absence of CP factors. Therefore, sensitivity to possible CP-type qualifications is not expected. A novel question about motion may be answered by using its internal structure to map it onto a similar but more familiar situation. Motion information implicit in the internal structure of a situation reaches awareness by enacting the situation; the imaginary enactment may in turn occasionally spill over into physical enactment *in vacuo*.

To obtain evidence regarding these issues, we interviewed subjects on their experiences while answering questions concerning motion; we also explored the effect of changes in the problem situation. Issues examined include the frequency of experiencing an enactment of the problem, the stability and consistency of subjects' problem conceptions (which provides an index of the number and generality of knowledge elements employed), the use of analogies to familiar situations to comprehend unfamiliar problems,

¹For example, the sling conception might have an internal structure including a forward element, an outward element, a defined release point, and so forth. Most important, the conception might *not* make a distinction between circular and linear motion, or between motion and force.

sensitivity to likely CP restrictions, and consistency of conceptions across closely related problems.

Method

Subjects

Volunteers from Introductory Psychology classes responded to a one-page screening device containing the sling diagram and text (as given in McCloskey, 1983). Of these subjects, 33 were chosen so that a broad spectrum of response types was represented; these individuals were extensively interviewed. Ten had taken one or more physics courses in high school or college.

Basic problems

In addition to the sling problem, subjects were queried about the spiral tube problem (McCloskey, 1983, p. 300), in which a ball is shot through a tube coiled on a flat surface. The Newtonian response to this problem is a linear path tangent to the spiral, straight out of the spiral's exit.

While these problems were the initial ones given, several variations (see below) were employed as the interview proceeded.

Procedure

Interviews lasted from $\frac{1}{2}$ to $1\frac{1}{2}$ hr, with most lasting 1 hr.² During each interview, one author was designated the principal interviewer and had primary responsibility for directing the questioning; two to five others transcribed the subject's comments, and also interjected questions in order to clarify points or test their understanding of the subject's remarks. A transcribed comment was used in interpreting subjects' paths and beliefs only when it appeared in at least two transcriptions.

Subjects were presented with a series of sling and spiral diagrams while either the basic problem or a variation was read to them. They responded by drawing one or more paths of motion on each diagram. The sequencing and specific content of questions were contingent in part on the subject's responses to prior questions, so that the subject's beliefs and experiences could

²Some subjects were asked motion questions in addition to the sling and spiral. Their responses to these other questions will not be discussed here.

be fully explored. Consequently, most subjects received only a subset of the following problems and questions.

Questions

An important part of our hypothesis concerns the consistency of responses across variations in the two basic problems. We utilized two major types of variations:

(1) *Spiral versus sling*: In Newtonian mechanics these two problems are represented in essentially the same fashion, and the trajectories are the same. Because the forces at play in these two problems are so similar, a naive theory of any generality might represent them in the same way, thereby making responses to these two problems identical (although not necessarily Newtonian). In fact, McCloskey, Caramazza, and Green (1980) found that most subjects, even those giving non-Newtonian responses, did respond consistently across these two problems; they used this to support their contention that subjects have developed naive laws of motion. Including both problems in some interviews allowed an attempted replication of this finding.

(2) *Focus*: Other than the Newtonian response, the two other major response types the spiral and sling typically elicit are (a) curved, or (b) for the sling only, straight but at an angle much greater than 90 degrees, up to 180 degrees (a linear continuation of the radius of the sling at the point of release; henceforth we term this response *outward*). These response types might indicate relatively stable naive theories developed by different subjects. On the other hand, these major response types may be due to differences in subjects' momentary conceptions of the situation. These two alternative views of response differences can be tested by attempting to focus attention on aspects of the problem that were not originally salient to the subject. In our terms, one can attempt to change the subject's response by evoking a different prototype containing a different conceptual structure, thus producing an enactment that may contain a new trajectory. Only if response differences among subjects are due to differences in the conception momentarily evoked by the problem, rather than to differences in general theories, should it be possible to change an individual's response by momentarily focusing the subject's attention on previously unnoticed aspects of the situation. If response differences among individuals are due to differences in the general theories of motion each has developed, it should be quite difficult to change an individual's response, requiring a refutation of the subject's personal theory.

We developed four focuses empirically, from our discussions with the first few subjects who responded naturally with Newtonian, curved or outward responses. Once developed, each of the following focuses was added to the end of the basic problem statement to make a new problem variation.

(a) *Sling/outward*: This focus was designed to capitalize on the outward pull and relatively low velocity felt by a person being swung in a circle. Subjects were asked to take the point of view of the ball and to think about the forces they would feel just before and just after the release. The situation was compared to being swung around by the arms.

(b) *Sling/curvature*: This was intended to encourage subjects to forgo a distinction between curved and linear motion important in Newtonian theory, and to focus attention on the curved path of the ball before it is released. The conflation of curved and linear motion allows structure mapping of the problem onto examples of linear motion which by analogy yield curved motion in the sling problem. To encourage this mapping subjects were reminded that when something (such as a toy car or ball) is pushed or thrown, it usually continues to move along its path, but this motion gradually subsides. The circular motion of the ball in our problem was emphasized by having subjects trace the motion of the ball around the circle once before responding.

(c) *Spiral/linear*: Subjects naturally giving curved responses on the spiral problem seemed to imagine the ball was spinning as it emerged. Because spin can impart curvature to a path (the so-called Magnus effect), it could be an experiential source of curved paths. We therefore asked subjects to consider the problem when the object shot through the tube was a bullet rather than a ball. In this case curved paths should be less frequent because the bullet is unlikely to roll through the tube, and is thus unlikely to be spinning as it exits.

Subjects naturally giving a Newtonian response also believed the orientation of the exit was the only important element of internal structure in determining the path. Therefore, language emphasizing the spiral's exit was included in this focus.

(d) *Spiral/curvature*: Here the subject was encouraged to focus on the spiral path of the ball in the cylinder (instead of the exit) and to include spin in the enactment, induced by the ball rolling along the outer wall of the spiral. Subjects were asked to imagine being inside the ball, and to imagine the forces they would feel as the ball is forced by the outer wall of the tube to travel a curved trajectory.

For both sling and spiral, subjects responded to one or more of the focus problems after presentation of the basic problem.

In addition to the problems and variations described above, there were five standard questions asked of subjects:

(a) Immediately after the first problem, and at other appropriate points, the principal interviewer said, "You paused for a moment before responding. What were you thinking? What was going on inside your head when you came up with an answer? Please describe it as best you can." If necessary the interviewer continued, "How did you come up with a response? What did you do? Where did the response come from?" Our intention was to elicit a description of the subject's conscious experiences during the usual pause between problem presentation and response.

(b) Subjects were asked to explain or justify their responses. These were used to infer some of the internal structures of the conceptions used by subjects.

(c) To examine understanding of factors which are part of the CP clause in Newtonian physics, subjects were asked to take into account the effects of air resistance and/or friction, and to contrast this situation with the original question where they were asked to ignore these factors. Toward the same end, subjects also responded to a sling described as under water, and to a sling described as a feather on a thread.

(d) To examine the effect of velocity in determining responses, subjects were asked what would happen if the ball (or substitute object) were going faster, or slower, than they had originally assumed.

(e) At the end of the session, each subject was asked directly about enactment, that is, whether she or he had solved problems by experiencing events mentally, seeing things happen "in the mind's eye," and so forth.

Results and discussion

Our major claims are that subjects have the conscious experience of enacting the situations presented in the problems, and that their responses come directly from the enactment. We therefore first examine descriptions of conscious experiences.

Enactment

Most subjects spontaneously give strong indications that they experience enactments of the situations presented to them (see Table 1). Some typical comments were: "That's just the way I see it happening ... I was following what the ball was doing ... I visualize it in my head ... I pictured myself throwing the ball ... I saw it go like that ... I was trying to picture it ..." In response to the direct enactment question at the end of the session (question e) only two responded equivocally ("I'm not sure what you mean," and

Table 1. *Percentage of responses to sling and spiral possessing specified characteristics*

Characteristic	<i>n</i> ^a	%
Experience of enactment		
Spontaneous	(33)	79
In response to question at end	(33)	94
Inconsistency		
Across basic problems	(15)	87
Across Focus		
Physics background	(6)	0
No physics background	(15)	73
Friction		
Extreme responses to feather, & under water	(16)	63
Air resistance		
As wind	(18)	61
Newtonian	(18)	22
Structure mapping		
Spontaneous analogies to familiar situations	(33)	48
Compromise conception of sling		
Speed affects path	(16)	87

Note. Percentages are based on the number of subjects who were asked questions relevant to determining a listed characteristic, rather than on the total number of subjects.

^a The number of subjects whose responses were relevant to determining the listed characteristic.

“Maybe”). The usual reaction to the direct question is well represented by the response of one subject who had given no spontaneous signs of enactment: “Of course I was seeing it happen in my head. How else could I answer your questions?”

Nine of the subjects used small amplitude hand and body motions during the pause between problem presentation and response. When queried, subjects indicated these motions were connected to their thoughts about the problem. These gestures may be *in vacuo* physical enactments spilling over from mental enactments.³

³McNeill (1985) describes similar “iconic” hand gestures during story telling and attributes them to inner speech, which he considers a common source of both speech and gesture. McNeill supports this conclusion by noting that such gestures never occurred in the absence of speech in his observations. However, this correlation is likely an artifact of the observational situation (story telling). None of our subjects used language while employing these iconic gestures; most remained silent, staring into space or at the diagram. While we do not deny there is a connection between language and gesture, we suggest that hand and body gestures may reflect internal actions and events the subject is experiencing. We propose that the common source of overt language and gesture is enactment, rather than a quasi-linguistic inner speech.

Variations

Given that the conscious experience of enactment occurs to nearly all the subjects, the next question is whether the enactment has a functional role, or is mere epiphenomenon. Can changing the subject's enactment cause major changes in the response? Throughout the following, the criterion for a change in path is a change from one to another of the major alternative paths (Newtonian, curved, or outward):

(1) *Sling versus spiral*: Of the 15 subjects tested on both basic problems, most (87%) were inconsistent (see Table 1). These findings fail to replicate the consistency found by McCloskey et al. (1980). The high rate of inconsistency is evidence against the use of principles general enough to subsume both problems.

(2) *Focus*: Focusing the subject's attention on aspects of the situation was generally effective in changing the responses of those without physics tutoring, but ineffective with those who had taken one or more physics courses in high school or college.

Of the six tested who had some physics background, none were affected by our attempts to change the focus of attention, although some were tempted to change. On the sling, one said, "You have started me thinking ... maybe it could curve," and another said, "If I hadn't had physics, I would think it curved."

For the 15 untutored subjects tested, 11 changed their answers to the sling and/or the spiral when given a focus contrasting with their original answer. (Out of the nine given focus alternatives for both sling and spiral, seven changed their answers on both, and two changed their answers on one but not the other.)

Surveying the results from both types of problem variation, subjects' responses do not appear to be governed by any consistent rule or principle. It is clear that changes in the enactment, resulting from variations in the situation portrayed in the problem, can often cause major changes in subjects' responses. This suggests that an enactment of the situation is the true source of the response. The ease with which enactment can be changed suggests that the enactment itself is generated from relatively specific and numerous prototypes, rather than from a few abstract principles with sufficient generality that they yield the same analysis of a wide variety of situations.

On the other hand, if one insists that knowledge must be systematic, connected, and abstract, inconsistencies on problems of physical motion can be treated as mere asynchronism or temporary cognitive heterogeneity. An

analogous situation arises in cognitive development, in which the Piagetian approach appears to predict consistency across tasks and an ordering of development through time that is frequently absent. It is often noted, however, that such inconsistencies are not incontrovertible evidence against the Piagetian approach (Flavell, 1982; Gelman & Baillargeon, 1983; Pinard & Laurendeau, 1969; see Nussbaum & Novak, 1976, for an example of this approach to the development of a physical concept similar to the concepts tested here). Likewise, the theory approach to motion knowledge is not absolutely refuted by the absence of consistency across all questions of motion, because a variety of performance factors might obscure the principled competence of research participants. Furthermore, whether two responses are inconsistent depends in part on whether subjects consider the problems to be the same. If two problems such as the sling and spiral are treated as being nonequivalent, different sets of principles may be applicable.

However, these qualifications do not completely extricate the theory view from difficulties. We have shown frequent inconsistent responses to two closely related problems that have previously produced consistent responses that were taken as evidence for general principles. Furthermore, major inconsistencies occur within a subject when only the focus of a problem (not the problem itself) is changed. These inconsistencies appear especially difficult for a theory position to account for, since principles must be narrow indeed to produce completely discrepant responses in such a limited problem domain.⁴

Although these findings do not rule out the naive theory position altogether, a theory approach which allows the degree of inconsistency we find has given up one of the major empirical claims that differentiates it from other positions, and is thus in danger of becoming formally equivalent to the prototype approach. Regardless of one's interpretation of the evidence, it is undeniable that inconsistencies are ubiquitous in many domains of knowledge, and subjects' responses to many sorts of problems are situation-specific. These points suggest that the traditional model of systematic knowledge can profitably be exchanged for one where knowledge consists of relatively unsystematic (incompletely connected and incompletely consistent), relatively numerous, situation-based "patches" of knowledge.

⁴It might be argued that the focus variable merely confuses subjects, or suggests alternative responses to subjects, who acquiesce. However, the focus conditions explicitly suggested only new conceptions, not the expected alternative responses themselves. Acquiescence is therefore not a viable explanation of why changes in focus produced the expected responses. In general our view is that the responses subjects are willing to make are governed by the conceptions of the problem they are able to adopt, which in turn are governed by the internal structures of the prototypes subjects bring to bear on the problems. We therefore believe the attempt to focus subjects' attention on various aspects of the problem is a legitimate technique for revealing the repertoire of available prototypes.

Friction

For the feather and the underwater variants of the sling problem, subjects frequently responded that the sling would drop straight down or drift randomly, even though they were reminded during the problem to ignore air resistance and friction (see Table 1). This result demonstrates that individuals find it nearly impossible to isolate and ignore these aspects of the situation, as would be expected if responses are based on past experiences, where air resistance is inextricably intertwined with other elements of the situation, rather than abstract principles, where failure to extract friction as part of the CP clause leads to principles of severely restricted generality.

When asked to directly consider the effects of air resistance on the path of the ball in the sling or spiral, a majority construed air resistance as wind or moving air (see Table 1), either by stating so directly, or by asking from which direction we intended the air resistance to come, and so forth. (For these subjects, naturally enough, air resistance deflected as well as impeded the motion of an object.) One person considered air resistance and gravity inextricably linked (cf. Minstrell, 1982), and two gave uninterpretable responses. Only four subjects took the Newtonian position that air resistance can impede but not deflect motion.

To discover other CP clauses, we frequently asked each subject whether there were other factors that could influence the path of the projectile, or other information they needed in order to answer the question. These queries were unsuccessful in eliciting any general exceptions or factors which must be ignored.

These results do not rule out a naive theory constructed of principles but they do call into question the maximum generality such principles could possess. The friction concept, a portion of the Newtonian CP clause which is very important to the generality of Newtonian laws of motion, is rarely spontaneously constructed by untutored individuals. This makes it less likely that these individuals could possess naive principles of any generality. If individuals do develop general naive theories, they must also develop a CP clause, other than the Newtonian one, that we have not discovered and that our subjects cannot verbalize.

Structure mapping

Although no probe questions were designed to elicit structure mapping, subjects spontaneously mentioned responding to the problems by referencing subjectively similar past experiences (see Table 1). For the sling, examples included the hammer throw, shot put, and a baseball self-pitch machine. For

the spiral, subjects mentioned amusement park rides, circular slides, and water slides.

Problem conceptions

Thus far we have said relatively little about the internal structures we claim subjects impose on these problems. Subjects' responses and comments, and the success of the Focus variable, suggest some possible internal structures:⁵

(1) Many subjects think of the sling problem in terms of a compromise among opposing elements of internal structure (Caramazza et al., 1981, also noted this conceptual structure). These elements⁶ include forward motion, outward pull, and sometimes the inward pull of the string prior to release. This conceptual structure is especially clear in those giving outward responses, but even those giving curved and Newtonian responses show signs of it. The most direct evidence for the compromise conception comes from two subjects who explicitly volunteered it. When the idea was described to two other subjects, they emphatically agreed that it accurately represented their conceptions of the sling problem. For three additional subjects, discussing outward pulls made their answers more outward, indicating they also held this conception of the problem.

An indirect test of the compromise conception involves varying the imagined speed of the ball in the sling problem. When the path is conceived as the product of the two opposing elements, and depending on whether forward motion or outward pull is most salient to a subject, an increase in speed will strengthen that component and change the path accordingly. Table 1 shows that most subjects tested with these questions thought that a ball going faster than they originally assumed would have either a path closer to the depicted circle (focus on forward motion) or a path further away (focus on outward pull), indicating that subjects do appear to analyze the situation into these two components. One subject who at first thought speed would affect the ball's path evidenced this conception by eventually deciding aloud that any change in speed affects forward motion and outward pull equally, so that no change in path would occur with a change in speed.

⁵Others might wish to interpret the evidence in this section in the framework of a naive theory or mini-theories, rather than as reflecting the internal structures of prototypes. This strategy is not ruled out by our evidence, and it might prove to be a fruitful direction to pursue. In our opinion, however, the analogy to standard conceptions of scientific theory becomes so stretched here as to be marginally useful.

⁶We use the generic term element because our subjects did not ordinarily have separate concepts for motion and force (but see Clement, 1982, for a different interpretation).

It is especially significant that two out of the four subjects giving Newtonian responses and tested for sensitivity to speed responded with a change in path. Even though they gave the "correct" answer, they were not giving a Newtonian analysis to the situation, in which velocity does not affect the trajectory.

(2) Some responses indicated that some curved and extreme outward paths for the sling might be due to confusion over the release point. The release of a hand-held sling ordinarily includes a complex approach to the release point, a wrist snap, and a follow-through. If subjects are deriving responses from enactments of this event, they might be uncertain about the point in this sequence to designate as the release. If the release is defined to occur before or simultaneous with the wrist snap, one would quite legitimately draw a path that initially curves (as the ball is brought to the front by the wrist action), then gradually straightens. This thinking was indicated by one subject who spontaneously gave an outward path "if the ball is just released" but a curved and forward path "if the ball is thrown."

Alternatively, one might define the release to occur at the end of the follow-through (at least part of which in fact occurs after physical release). Because the follow-through is ultimately directed at the target in throwing a sling, the appropriate path under this definition of release is a continuation of the radius of the ball's orbit (the outward response). One subject showed this thinking when he claimed he answered the question by imagining a hammer throw, where the body in fact follows through after true release to face the target: His response was a continuation of the radius.

The internal structure of the spiral differs from that of the sling in that forward motion is much more salient, outward pull much less salient or completely absent, and the release point (at the mouth of the tube) is unambiguous. Many subjects explicitly focused their attention on the orientation of the mouth of the tube in explaining their response; this, they felt, was the only component of the tube that was important in determining the path. Outward responses never occurred in the spiral. Thus, despite their equivalence in Newtonian physics, subjects give the spiral and the sling very different conceptions.

(3) In some conceptions of the sling and spiral, curved motion is treated as correlative with linear motion, rather than as categorically distinct and exceptional, as it is in Newtonian theory. This hypothesis is supported by the success of the circular focus, where the distinction between the two types of motion was purposely obscured. It is also supported by the notion that the curved motion of the sling gradually straightens – that is, that it gradually "dies out," as does linear motion. No subject was directly questioned concerning this, but seven subjects indicated they held this belief, either verbally ("the faster it goes, the more the curve persists" on the sling) or in their

drawings. Furthermore, on the spiral, two subjects drew paths with unmistakable curvature while saying "it will come out straight." This last phenomenon is striking evidence of a failure to distinguish curved and linear motion.

McCloskey (1983) has attributed some similar observations of curved paths to a naive curvilinear impetus theory. His reasoning assumes that subjects categorically distinguish between curved and linear motion (as in Newtonian theory), an assumption that seems unjustified without further evidence.

(4) Another source of curved paths may be spin present in the objects of the enactment. Of five subjects who were asked to directly consider the effect of spin on the ball in the spiral, three changed their responses from Newtonian to curved, one exaggerated her curve, and one retained the Newtonian response.

Also favoring this hypothesis is the success of the curvature and linear sling focuses. Even though the problem language was not explicit concerning the manner of motion, many subjects in the spiral curvature focus mentioned imagining themselves *rolling* through the spiral (thus, we assume, exiting with spin). For the linear focus, subjects initially giving curved responses tended to straighten them when asked to imagine that the object being shot through the tube was a cylinder, an object we chose because it is unlikely to roll through the tube. One subject was explicit concerning his linear response to the basic problem: "Since the ball won't be spinning, the path will be straight."

Within a Newtonian framework curved paths, and their mental association with spin, are quite puzzling. Because they are incompatible with the concept of inertia, paths that are curved in the absence of any force should ideally never be observed in nature. Therefore (from this viewpoint), subjects' curved responses must be based on something other than empirical observations. To account for curved responses, McCloskey (1983) proposed that individuals develop a curvilinear impetus principle, which maintains that curved motion persists after the force initially responsible for curvature is removed. By definition, a general principle of this sort, however it is developed, allows subjects to respond to problems such as the spiral without relying on past experience or observation; it can explain the occurrence of physically unobservable responses to motion problems.

However, this argument for naive principles is flawed. Newtonian theory relies on a billiard ball world where instantaneous forces are applied to perfectly elastic objects on frictionless surfaces. In reality friction and gravity must be taken into account, and these forces are rarely instantaneous. A spinning object on a surface or in a medium such as air often experiences continuous forces that cause it to curve. A spinning object on a horizontal surface in a gravitational field (such as a top, or a ball after exiting from a

spiral) generally traces a curved path rather than a linear one, a readily observed phenomenon known as precession. Spin can also cause curved paths for objects in flight, such as the curveball in baseball, golf balls that hook, slice, and loft, tennis balls with "English," and so forth. In aerodynamics this phenomenon is known as the Magnus effect and is due to the viscosity of a medium moving across a spinning surface (Wegener, 1986).

The association of spin and curved paths evident in some responses to the spiral therefore suggests that curved paths may be due to observations made by subjects, as well as to the failure to distinguish curved and linear motion. In this view curved paths in the spiral might readily arise from motion prototypes with solid observational (but not empiricist) foundations⁷ rather than from a naive principle of curvilinear impetus (McCloskey, 1983).

Even though our instructions to consider spin were effective in changing the enactment to produce a curved path, the opposite instruction to ignore spin has been found by others to be ineffective. McCloskey and others frequently obtain curved responses on the spiral, even when subjects are instructed to ignore spin. Although difficult to understand in terms of a naive theory, where spin either is or is not part of the CP clause, this asymmetry in the effects of spin instruction is quite consistent with the enactment notion. Subjects responding to the spiral problem with past experiences in mind where spin and curvature were present will produce curved paths. However, unless these individuals understand that the curvature in those experiences is due to spin, the instruction to ignore spin will not eliminate curvature from their paths. On the other hand, the instruction to consider spin may encourage additional subjects whose initial responses were linear to think of those situations where spin, thus curvature, are indeed present, producing additional curved responses. In short, the efficacy of the instruction to ignore spin depends upon an understanding of the causal connection between spin and curvature, whereas the efficacy of the instruction to consider spin depends only on the co-occurrence of spin and curvature in prototypes.

Considering the general proposal that individuals possess conceptions of physical situations, it may seem that these conceptions make the prototype approach equivalent to the theory approach. In a loose sense of the term theory, one's conception of a situation can be considered a mini-theory. How-

⁷The fact that the spin subjects probably imagine in the spiral problem would lead to a curved trajectory the opposite of that given by most subjects is not counterevidence to this hypothesis. We do not propose that subjects know in detail which joint observations of curvature and spin are validly mapped onto the spiral problem, merely that an association between spin and curved trajectories exists in those prototypes some subjects map onto the problem.

ever, the conceptions we propose are situation-specific, and individuals appear capable of adopting several mutually incompatible conceptions for a single situation. In these respects conceptions are far removed from the broad principles of a scientific theory. The analogy to scientific theory implied by the theory position is not a useful description of such conceptions.

General discussion

Two general conclusions can be drawn from the evidence presented. First, it appears that the act of generating a solution to a motion problem includes experiencing an enactment. Second, subjects' responses are highly inconsistent in several respects. Enactment alone neither supports nor weakens the theory position, but inconsistencies in subjects' responses indicate that enactment cannot be generated by an unadorned naive theory based on general principles.

At this point there are various strategies for preserving the analogy to scientific theories, the heart of the naive theory view. Inconsistencies might not be incompatible with the theory view if unfamiliar problems are solved with a naive theory composed of general principles, while familiar problems are solved by relying on past experience. Kaiser, Jonides, and Alexander (1986) have recently proposed a dual approach of this sort. If some of our problems were familiar and others unfamiliar, a dual approach might explain some of the inconsistencies found.

However, it is not apparent that any of our problems are especially familiar (especially compared to what Kaiser, Jonides, & Alexander, 1986, propose). Furthermore, subjects frequently used structure mapping to solve the (clearly unfamiliar) unaltered sling and spiral problems – just those problems where a naive theory should be used, if it is available. The dual approach therefore appears unable to account for our results.

But there are other ways of preserving the theory approach. There is the possibility that some subset of individuals does possess and use a naive theory of motion based on very general principles. McCloskey (1983) has shown that some subjects are able to verbalize principles similar to those of the medieval impetus theory. Our own observations suggest that students in elementary physics courses often interpret Newtonian principles in a fashion similar to the impetus theory. Physics courses may sometimes paradoxically promote the development of naive personal theories.

Finally, one could propose (McCloskey, personal communication) that naive theories are composed of principles of some greater (but as yet unknown) degree of specificity. These principles could be used to generate the

enactments subjects experience. A set of rules of application (or restriction rules) could be developed to govern the deployment of these less general principles over situations.

Without further development the merits of this suggestion are unclear. The degree of inconsistency observed among problems that were drawn from a relatively narrow domain of motion phenomena suggests that the applicable principles would be so specific and so numerous as to bear little resemblance to traditional scientific principles, and a much closer resemblance to situation-specific prototypes. A naive theory composed of principles functionally equivalent to mental objects would be of little interest.

We prefer the prototype view to account for subjects' solutions to motion problems for two reasons. First, in the domain of physical knowledge (Karmiloff-Smith & Inhelder, 1974; McCloskey, 1983), and also in other domains such as biological concepts (Carey, 1985), and numerical concepts (Gelman & Gallistel, 1978), there is little direct evidence supporting the conjecture that subjects possess mental structures bearing the formal characteristics of a scientific principle. The strongest empirical claim of the theory position is that responses are consistent over some domain (McCloskey, Caramazza, & Green, 1980). We have found this point to be generally unsupported in the physical domain.

Other evidence used to support the existence of indigenous theories implicitly relies on the dichotomy between empirical and theoretical knowledge. The two forms of this evidence are that individuals' beliefs about the physical world often go beyond "mere observation of immediate empirical reality" (and thus cannot be due to empirical observations), and that they also diverge from standard scientific doctrine (and thus cannot be due to explicit tutoring in the physical sciences). If one accepts the theoretical/empirical dichotomy, the only remaining alternative is a personally developed naive theory. But without the dichotomy (which we reject), other knowledge forms become possible, and these two lines of evidence become rather slender reeds on which to support mental entities that are similar to traditional scientific theories in specific and substantial ways.

Consequently one might choose to maintain the theory position but abandon the analogy to traditional scientific theory. But then the claim that individuals possess theories becomes uninformative, equivalent to the claim that human beings possess notions, thoughts, beliefs, and so forth.

The second reason we prefer the prototype view is because it accounts parsimoniously not only for inconsistencies but also for many other phenomena accompanying solutions to motion problems. Referring to the characteristics of the theory and prototype approaches listed in the introduction, we find that, in agreement with our expectations based on the prototype

approach, subjects frequently experienced mental enactments, and these were occasionally associated with physical enactments as well. Responses were frequently inconsistent across similar problems and even within a problem when various attributes of the situation were selectively emphasized. Analogies to familiar situations were often spontaneously mentioned. There was no evidence of analysis of a situation into ideal versus contingent factors of the sort necessary for the application of a general principle restricted by a CP clause.

But if conceptions of motion are based on prototypes, which are in turn based on experience, why are subjects' solutions to motion problems so different from the Newtonian view, widely accepted as observationally correct for the macroscopic world, and why are they similar to the medieval impetus theory? Caramazza et al. (1981) have expressed surprise that indigenous ideas about motion diverge so drastically from what they assume to be an observationally correct theory (the Newtonian view), pointing out that subjects' naive theories are "often strikingly at variance with the most fundamental physical laws" (pp. 117–118), and by implication at variance with empirical observations available to observers.

But the Newtonian theory was originally primarily a celestial theory and is not by itself observationally adequate in the situations ordinarily accessible to common observation. Were untutored individuals to possess a theory of motion, it seems unlikely that it would be Newtonian, since almost all observations near the surface of the earth strongly contradict the Newtonian view. For instance, it is inappropriate to employ the arbitrary frames of reference of Newtonian theory, when the earth and the large bodies on it are for practical observational purposes fixed. Consequently there are important differences between motion and rest. Moreover, frictional forces which Newtonian theory considers separately are always present and are essential to all aspects of life on earth; there is little motivation to consider frictional forces as a separate category. These differences between the world in which humans live and the world portrayed in Newtonian theory seem to account for the major differences between Newtonian and "naive" conceptions of motion, and to account for the similarity between ordinary conceptions and the medieval impetus theory (which, significantly, was primarily an attempt to account for near-earth observations—the heavens were often thought to be ruled by a separate body of laws) noted by McCloskey (1983).

From this point of view, there is nothing particularly true or fundamental in Newtonian theory; it is simply a useful quantitative conceptualization of the macroscopic universe, especially the motions of celestial bodies. When the quantitative aspect is not needed, and when observations and predictions are confined to areas accessible to ordinary people, the medieval theory, and our subjects' views, seem more useful.

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Résumé

Les personnes qui n'ont pas de connaissances particulières en physique donnent parfois des réponses à des questions sur le mouvement qui sont cohérentes mais qui violent très nettement les théories physiques couramment admises. Cela pourrait vouloir dire qu'elles ont formulé des théories personnelles "naïves" du mouvement, et qu'elles en déduisent les réponses aux questions qu'on leur pose. Cependant, des entretiens avec des sujets à qui l'on demande de résoudre des problèmes de mouvement ont montré que la résolution du problème est subjectivement vécue comme le résultat d'une mise en scène mentale de la situation, et non comme une déduction à partir d'une théorie donnée. La source de la mise en scène semble être un ensemble de prototypes relativement précis, mutuellement incompatibles, qui représentent des aspects typiques du mouvement, et non une théorie composée de principes généraux. Les sujets résolvaient des problèmes sur des situations inhabituelles en élaborant des analogies avec des situations plus familières. Bien que les individus semblent acquérir un savoir qui constitue en quelque sorte une "théorie" du mouvement, nos résultats s'opposent au point de vue qui veut que ces théories soient composées de principes semblables à ceux des théories scientifiques.