In the Proceedings of the Sixteenth Annual Conference of the Cognitive Science Society. Hillsdale, NJ: Lawrence Erlbaum, 1994.

Imagistic Simulation and Physical Intuition in Expert Problem Solving

John Clement
Scientific Reasoning Research Institute
Hasbrouck Laboratory
University of Massachusetts
Amherst, MA 01003
413-545-5864 or 0988
Clement@srri.umass.edu

Abstract

This paper discusses evidence from thinking aloud case studies indicating that part of the knowledge used by expert problem solvers consists of concrete physical intuitions rather than abstract verbal principles or equations. One purpose of the paper is to provide empirical documentation of behaviors such as spontaneous references to using intuition, depictive hand motions, and dynamic imagery reports. Although the role of imagery in lower level tasks is becoming more accepted, we currently lack sufficient empirical evidence for its use in higher level thinking. In order to account for cases where subjects appear to be "running a simulation" of an event on the basis of a physical intuition, a model is presented in which a somewhat general and permanent perceptual motor schema controls a more specific and temporary image of a situation. This process is termed "imagistic simulation". The imagery can be kinesthetic as well as visual, and dynamic rather than static, suggesting the involvement of the motor system. Although rules for making inferences from networks of causal relations have been studied, we lack models which analyze the nature of mental simulations underlying a single causal relationship. Such physical intuitions and simulations may provide basic building blocks for constructing visualizable models in science.

Issues in the Areas of Simulation and Physical Intuition

Expert knowledge in science is commonly described as predominantly abstract. For example, Chi, Feltovich, and Glaser (1981) state that experts in physics use: "abstract physics principles to approach and solve a problem representation." Concrete features are used at an early stage in the solution to activate more abstract principles. (p. 121). Novices, on the other hand, "base their representation and approaches on the problem's literal features. . ." (p.121). Whether or not it was the intention of these authors, their findings have contributed to the common perception of expert thought as predominantly abstract. This characterization of experts appears to conflict with reports of scientists such as Einstein's: "The words or the language. . .do not seem to play any role in my mechanism of thought. The. . elements in thought are certain signs and more or less clear images . . . of visual and some of muscular type." (quoted in Hadamard, 1945, p. 142-43.) In this study I investigate whether concrete, non-abstract knowledge can play an important role in expert thinking. Work in this area is also motivated by recent studies in: (1) the important cognitive roles played by actions involved in scientific experimental practice (Tweney, 1986; Gooding, 1990) and (2) imagery in science (Nersessian and Greeno, 1990; Miller, 1984; Qin & Simon, 1990.)

Whereas a good deal of prior theoretical work in artificial intelligence has been done on complex forms of simulation involving inferences on networks of causes with many links (e.g. de Kleer and Brown, 1983; Forbus, 1984), very little attention has been given to analyzing the nature of the "atoms"--here viewed as elemental imagistic simulations involving a single causal relationship--that underlie and make up these networks in humans.
Descriptions of processes involved in elemental mental simulations may provide a foundation for helping us understand more complex processes such as reasoning via scientific models, analogies and thought experiments.

Initial Examples of Physical Intuition

In this study advanced doctoral students or professors in technical fields were asked to solve the "Spring Problem" shown in Figure 1.

A WEIGHT IS HUNG ON A SPRING. THE ORIGINAL SPRING IS REPLACED WITH A SPRING

- MADE OF THE SAME KIND OF WIRE,
- WITH THE SAME NUMBER OF COILS,
- BUT WITH COILS THAT ARE TWICE AS WIDE IN DIAMETER.

WILL THE SPRING STRETCH FROM ITS NATURAL LENGTH, MORE, LESS, OR THE SAME AMOUNT UNDER THE SAME WEIGHT? (ASSUME THE MASS OF THE SPRING IS NEGLIGIBLE COMPARED TO THE MASS OF THE WEIGHT). WHY DO YOU THINK SO?

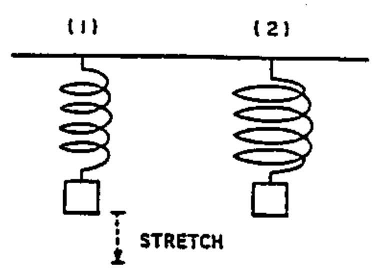


Figure 1: Spring problem.

By "expert problem solver" in this context, I mean a person who is an experienced problem solver in a technical field. Most subjects were not experts on the specific content domain of the theory of static forces in springs. All sessions discussed in this chapter were videotaped except subject S5, who was audiotaped. The correct answer to the spring problem is that the wide spring will stretch farther.

Two examples of solution episodes that appear to involve physical intuition are:

> 027 S1: You don't have to know any formulas to see that ... God almighty! Of course it [the wider spring] goes way down. You know. How could it do otherwise?...That's a seat-of-the-pants feeling I would trust beyond any of it.... I would bet a thousand to one.

To counter the idea that physical intuitions are used only by those who lack more formal reasoning capabilities, it should be noted that this subject is a Nobel laureate in physics. However, most subjects did not have so strong an intuition about the target problem itself, but had intuitions about analogous problems. For example, subject S3 considered the analogous case of weights on the ends of long and short horizontal rods:

> 010 S3: My intuition about that is that if you took the same wire that was fastened on the left here [short horizontal rod] and doubled the length ..that ..it would bend considerably farther.

He then attempts to transfer this intuition to the case of the spring, using it as the basis of his prediction that the wider spring will stretch farther. (See Clement [1988, 1989] for discussion of reasoning from analogies to such intuitions.)

Intuition reports. Both excerpts above contain an example of what I call a physical intuition report, where the subject reports using an "intuition" or uses terms that indicate they are proceeding primarily on the basis of a nonformal "feeling" or "sense" of what will happen to a physical system. In natural language the word "intuition" unfortunately has multiple meanings that refer to both knowledge structures and nonformal reasoning processes. I will avoid the latter use here, so that I will not use the term physical intuition for processes such as induction by enumeration, analogical reasoning, or heuristic strategies for problem solving. Instead, I will focus on elemental knowledge structures seen as basic units of knowledge, as in the examples given so far. I call these "elemental physical intuitions".

Defining Features and Observable Behaviors Associated with Physical Intuitions

On the basis of transcripts like those above, one can point to a basic cluster of phenomena that suggests the existence of physical intuitions as a type of natural cognitive structure. Defining properties for physical intuitions are underlined below, along with observable properties that can indicate them. diSessa (1983) refers to certain kinds of similar knowledge structures as "phenomenological primitives". I will use the term elemental physical intuition here in a way that shares several of the features of a phenomenological primitive, including the following ones.

> Knowledge structures. A physical intuition is a knowledge structure that resides in long term memory and that can be activated to provide an interpretation of or an expectation about a physical system.
> Explanation, justification unnecessary. Subjects often refer to a physical intuition as a starting point and do not express a need to further justify derive, or explain it.
> Modest generality. The situation referred to by subjects is often more general than the memory of a specific incident. As diSessa points out however, the degree of generality is not nearly so large as that of the concepts used in Newtonian mechanics.

In addition to the features identified by diSessa, I also point to some other characteristics below, and to the imagery reports that often accompany the use of intuitions.

> Intuition reports. In thinking about a physical system, subjects sometimes spontaneously report making a prediction based on an intuition (termed an intuition report). However, we cannot attach too much importance to a subject's use of the term, since, for one thing, its meaning in natural language is so broad and vague. Therefore this observation should probably be used only in conjunction with others.
> Self-evaluated. Strength of belief in a physical intuition is described as being determined largely via internal criteria rather than being dependent on the evaluation of an authority.
> Oriented to concrete objects. Subjects speak of an intuition as providing knowledge about objects and manipulations of or relationships between them, rather than a symbolic result that must be interpreted.

Imagery Reports and Imagistic Simulation

In this section I present evidence indicating that the use of a physical intuition can involve dynamic imagery. One source of difficulty here is that most discussions of imagery involve visual imagery alone, whereas physical intuition often appears to involve imagining actions taken on objects as well.

Imagery Reports

In the cases to be examined below subjects spontaneously use terms like "imagining," "picturing," "hearing," a situation or "feeling what it's like to manipulate" a situation." I refer to such statements as imagery reports. These refer to several sensory modes, including kinesthetic imagery. In contrast to most of the literature on imagery, I am concerned here with spontaneous imagery reports where the interviewer does not ask the subject whether an image was used. For example, S2, thinking about the related problem of comparing short and long springs says:

041 S2: "I'm imagining that one applies a force closer and closer to the origin [top] of the spring, and. . .it hardly stretches at all."

Based on the work of Shepard (1984), Kosslyn (1980), and others, in hypothesizing the use of imagery in these subjects

I mean a temporary spatial representation capable of representing in at least a skeletal manner: (a) the shapes of objects (b) spatial relations among them and (c) object movements over time. This spatial representation may use some of the brain's higher-level perceptual processing capacity which makes available various manipulation processes (orienting, transforming and combining images) to these subjects. Recently Shrager (1990) has argued that perception and perceptual experience form the basis of conceptual knowledge.

Imagistic Simulation Processes

However we have still not provided an explanation for how new knowledge can emerge from a new combination of an intuition and an image. The following example provides an example of this. At this point the subject has decided that a twisting deformation in the wire is one of the consequences of stretching the spring. (Twisting of the wire and the resulting torsion do in fact play a predominant role in determining the behavior of a spring.) He is trying to decide what effect widening the spring will have on the twisting deformation by imagining himself twisting straight horizontal rods:

> 137 S2: . . .if I have a longer rod, and I put a twist on it, (moves hands as if twisting a rod - see figure 3) it seems to me --again physical intuition--that it will twist more. Uhh, I'm - I think I trust that intuition.
>
> 138 I: Can you stop thinking ahead and just think back on that; what that intuition is like?
>
> 139 S2: Oh, I have a kinesthetic intuition. . . I'm imagining holding something that has a certain twistiness to it and twisting it.
>
> 141 S2: Like a bar of metal or something like that. Uhh, and it just seems to me as though it [a longer bar] would twist more.

The subject eventually uses this result as a central assumption in order to make inferences about the spring problem. Here one can observe a number of the phenomena under discussion: co-occurrence of an imagery report (line 139) and a stated prediction (137, 139), intuition reports (137, 139), and depictive hand motions (137). In addition line 139 contains an example of a dynamic imagery report, where the subject describes a situation in an imagery report as changing with time. The co-occurrence of intuition reports and dynamic imagery reports motivates proposing the hypothesis that physical intuition and imagery are used in tandem. It is hypothesized that the subject is going through an imagistic simulation process wherein an intuition schema assimilates the image of a particular object and produces expectations about its behavior in a subsequent dynamic image.

The diagram above the double horizontal line in Figure 2 gives an overview of this process. In this case it is assumed that the physical intuition about how an object behaves is an expectation embodied in a permanent and somewhat general perceptual motor schema. For S2 imagining twisting a rod above, the imagistic simulation is the process of applying a schema capable of controlling real actions for the twisting of actual objects in the world. Here, however the schema is applied to an image--a particular image of a one foot long bar of metal. (This initial image may have been generated in some previous "setup" process.) In the "running" process the schema assimilates ("locks on to") the image, "performs an (imagined) action on it" over a period of time on the order of .5-3 seconds (as indicated by the downward pointing dotted arrows), and generates an expectation about its behavior. In Figure 2 the terms below the double line denote observable behavior patterns in the transcripts that can provide evidence for the hypothesized cognitive structures and processes shown above the line. It makes sense that this process should require two major components: a more general schema that is a permanent resident in memory (this helps explain where the knowledge being used comes from); and a temporary image of a specific example (this helps explain how one is able to think about twisting a novel new example, such as the "dotted spring" in the next transcript below; in such a case the image may be assembled by drawing from a number of pre-existing, permanent schemas, but the composite image itself may be novel and need only be temporary.)

It is assumed that all of the cognitive processes shown in Figure 2 can be nonverbal in character. Since the subject is asked to think aloud as much as possible however, there must also be an auxiliary description process which enables the subject to describe his thinking after it occurs. This process is not shown explicitly in the diagram. (In actuality the subject presumably goes through *two* simulations with a short and a long rod here, after which he is able to compare them.)

The best evidence supporting the hypothesis that an imagistic simulation has taken place would be the co-occurrence of all the observable behaviors shown below the horizontal line in Figure 2. However, because subjects are not used to thinking aloud in this degree of detail, in practice we are only likely to see a small number in any one episode.

Precedents in the literature on perceptual motor schemas. A perceptual motor schema is hypothesized to contain at least three major subprocesses: a subprocess for assimilating objects in the environment based on preconditions that must be satisfied for the schema to apply; a subprocess for initiating and tuning or adjusting the action so that it is appropriate for this particular object; and a third subprocess capable of generating expectations about the results of the action - in this case, an image of how far the rod will turn. Perceptual motor schemas may not be the only structures responsible for physical intuitions, but in the examples discussed here they appear to serve as one very important type. The perspective that a motor schema can have generality through a pattern of actions and expectations over time with parameters adjusted to a particular situation in a process of tuning has precedents in Piaget (1976), Neisser (1976), and Schmidt (1982). Transcript observations supporting the view that perceptual-motor schemas are being used include: personal action projections (describing a system action in terms of a human action), kinesthetic imagery reports, and depictive hand motions. It is possible that the subject is able to focus on an implicit relation between variables that is embedded in the tuning function of a perceptual motor scheme and describe it explicitly for the first time in episodes like that of the twisting rod above. More details on how knowledge implicit in the physical intuition is converted into explicit knowledge is given in Clement (to appear).

Importance of Concrete Intuitions and Imagistic Simulation

The following protocol from a research physicist indicates that imagistic simulation is sometimes quite effortful. This episode comes after a follow up question from the experimenter about how one might determine that twisting is occurring in the spring:

> 022 S5: . . .suppose I had a big spring and I could make little paint dots on it all along its length....and saying ... would I see a torsional displacement of the paint dots. And what would it look like. And I have a hard time imagining that because you know, the torsional displacements that come to mind are very small.
>
> 024 S5: (Makes drawing of spring with paint dots on outside of wire)
>
> 036 S5: So. . .the other parts are going to twist such that . . . little dots on the surface will tend to move up. . .
>
> 038 S5: . . .The mass is going down and so now--these portions of the spring------Hmmmm
>
> 040 S5: . . .I'm just getting a hard time envisioning what's going on 3-dimensional space, and so I'm having a hard time seeing which way this wire is going to rotate.
>
> 041 S5: Well I want to imagine that the portion here up to the cross section..is fixed. So I'm pulling down on the weight or the weight's pulling itself down, and that's causing these coils to elongate. I'm trying to decide how it's gonna twist this portion of the wire . .

But eventually he is able to make a confident prediction:

> 042 S5: . . .if you imagine the extremes, if you pull it up and down, this little line. . .on the outside of the spring you know, would. . .rotate down till it's at the bottom.
>
> 046 S5: . . .I guess I'm-I'm quite satisfied with that.
>
> 072 E: Were you thinking about an equation there?
>
> 073 S5: Oh, no. This is all er, I think very experimental. What I think I have- this image of this line of paint dots on a spring and you know I'm pulling on the weight. I'm going pull and release, pull and release and so I'm constantly putting it through its paces. And asking you know, how would I see the dots move.

Since S5 makes a drawing of the spring in line 24, does that mean that it replaces and makes redundant any internal imagery that occurs? It cannot replace the imagery, since he speaks of imagining movements, and the drawings do not move. This makes it reasonable to assume that the drawing reflects and may support or perhaps even replace static features of the subject's initial image, but that it cannot replace any dynamic imagery.

Simulation can require effort, arguing that it is not epiphenomenal. The observations for this protocol then fit almost all of the patterns shown below the horizontal lines in Figure 2. These allow one to triangulate from multiple sources of evidence to support the hypothesis that the subject is running through imagistic simulations. In addition, he describes the simulation as a process extended over time, and makes a "personal action projection" by referring to his own pulling for the force of the weight. The fact that he: says "I want to imagine" the situation (41); says that it is difficult for him; makes repeated and extended efforts to do it anyway; and uses imagery enhancement techniques such as the "painted dots"; is evidence that: (a) he intends and tries to set up the imagistic simulation as an extended process very different from "remembering a fact"; (b) the process requires considerable effort; (c) the process of imagining is important to him as a technique. These findings, along with the fact that he "asks questions of" the simulation, and that he speaks of the simulation as the main technique used to give his answer, argue that the intuitions and imagery involved in the simulation are not simply unimportant side effects of some other process, but are effortful processes that are central to his thinking here. Thus he does not "get the physics for free" here, but must work hard to adapt and apply existing schemas in order to construct new situation in order to construct new knowledge. Although any one indicator such as an imagery report could be explained by another interpretation, the hypothesis that imagery is playing a role in the solution process acquires more substantial support when one can triangulate from a number of different observations in the same episode.

Dynamics. Why did subjects bother to run through effortful imagistic simulations? The fact that they did so supports the view that the simulations allowed them to apply knowledge that was not stored as a linguistic description. For if it were explicitly described, then why announce the intention to form an image of the situation and make the effort to run through a simulation of it? Why not just report it? The presence of dynamic imagery reports, hand motions, imagery enhancement techniques, and the effort put into imagistic simulations all support the view that simulations in this case are very different from descriptive, language-like representations. These observations and the subjects' reports of experiencing the effects of actions occurring over time (S5, line 73, S2 line 139) provide a real motive for using the term "simulation." They suggest that the subjects are somehow mentally simulating some aspects of the rich flow of perceptions and/or motor actions over time that would exist if they were actually viewing and/or causing such events. This is a different meaning for "simulation" than traditional descriptions of a symbol manipulation procedure which steps its way through a series of inference rules operating on a set of word-like tokens. The fact that the subjects are referring to only a single causal relation in these elemental simulations argues against the alternative view that they are making some kind of chain of reasoning inferences within the passages quoted. (Subjects may be able to assemble imagistic simulations involving multiple causal relations, but focusing on single relations here helps us contrast these findings with those from previous research.) I do not wish to deny the importance and nested power of modes of thought which depend on linguistic symbols and mathematics, or the idea that once a physical intuition is described, that such a description can be stored with the intuition schema. But the above findings reinforce the view of simulation as a thought process that can take place outside of a language-like representation, before it is translated into one. If this is correct, the intuitive knowledge developed in an imagistic simulation does not just consist of an end state of static tokens, but is a process or activity (or a readiness for such an activity) which takes time to experience and to have significance for the subject. In this sense the knowledge is dynamic.

Conclusion: Can Concrete Physical Intuitions and Simulations Play an Important Role in Expert thinking?

Much work remain to be done in this area. The exploratory case studies described here provide some initial evidence for framing the following hypotheses: (a) In addition to abstract principles, experts can use physical intuitions in imagistic simulations of concrete situations. These can play a role in problem solutions that is more than simply a "start-up" role or cues for abstract categories attached to rules. In particular they can play the important role of anchoring assumptions which underpin explanations constituting the subject's central understanding of a system. Thus, imagery and intuitions were part of the central argument in these solutions, not just side effects. (b) This conflicts with the common assumption that experts are characterized by their abstract knowledge. However, that may be partly because previous studies used problems that were easy or routine for the experts; here the experts were engaged in non-routine model construction. (c) Use of an intuition can involve dynamic imagery that is controlled by a perceptual motor intuition schema.

Implications. There is evidence that students also use physical intuitions. The literature on alternative conceptions in science provides many examples, and there is also evidence for useful intuitive preconceptions that can ground qualitative scientific models (Clement, 1993). Although the separation between expert and naive subjects is significant, the finding that experts use concrete physical intuition schemas makes it less sharp, and this expert-novice similarity suggests that physical intuition may play an important role in instruction.

Acknowledgments

This research was supported by National Science Foundation Grant #MDR-87511398 and MDR 9150002. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the National Science Foundation.

References

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

Clement, J. (1988). Observed methods for generating analogies in scientific problem solving. *Cognitive Science*, 12, 563-586.

Clement, J. (1989). Learning via model construction and criticism: Sources of creativity in science. In J. Glover, R. Ronning, & C. Reynolds (Eds.), *Handbook of creativity: Assessment, theory and research* (pp. 341-381). New York: Plenum.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, 30, 1241-1257.

Clement, J. (to appear). Use of physical intuition and imagistic simulation in expert problem solving. In D. Tirosh (Ed.), *Implicit and explicit knowledge*. Norwood, NJ: Ablex.

de Kleer, J. & Brown, J. S. (1983). Assumptions and ambiguities in mechanistic mental models. In D. Gentner & A. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

diSessa, A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Freyd, Jennifer, & Finke, Robert (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 10, 126-132.

Forbus, K. (1984). Qualitative process theory. *Artificial Intelligence*, 24:85-168.

Gooding, D. (1990). *Experiment and the making of meaning: human agency in scientific observation and experiment*. Dordrecht: Kluwer.

Hadamard, J. (1945). *The psychology of invention in the mathematical field*. Princeton, NJ: Princeton University Press.

Kosslyn, S. (1980). *Image and mind*. Cambridge, MA: Harvard University Press.

Miller, A. I. (1984). *Imagery in scientific thought: Creating twentieth-century physics*. Boston: Birkhauser.

Neisser, U. (1976). *Cognition and reality*. San Francisco: W. H. Freeman.

Nersessian, N. J., & Greeno, J.G. (1990). Multiple abstracted representations in problem solving and discovery in physics. In *Twelfth Annual Proceedings of the Cognitive Science Society*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Nersessian, N.J. (1991). Why do thought experiments work? In *Thirteenth Annual Proceedings of the Cognitive Science Society* . Hillsdale, NJ: Lawrence Erlbaum Inc.

Piaget, J. (1976). *The grasp of consciousness: Action and concept in the young child*. Cambridge, MA: Harvard University Press.

Qin, Y. & Simon, H. (1990). Imagery and problem solving. In *Twelfth Annual Proceedings of the Cognitive Science Society*, (pp. 646-653). Hillsdale, NJ: Lawrence Erlbaum. Inc.

Schmidt, R. A. (1982). *Motor control and learning.* Champaign, IL: Human Kinetics Publishers.

Shepard, Roger N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review,* 91, 417-447.

Shrager, J. (1990). Common sense perception and the psychology of theory formation. In J. Shrager and P. Langley, (Eds.), *Computational models of scientific discovery and theory formation* (pp. 437-470). San Mateo, CA: Morgan Kaufmann.

Tweney, Ryan D. (1986). Procedural representation in Michael Faraday's scientific thought. PSA 1986, Volume 2.

Witz, K. (1975). Activity structures in four year olds. In Scandura, J. (Ed.), *Research in structural learning,* Vol. II. New York: Gordon and Breach.

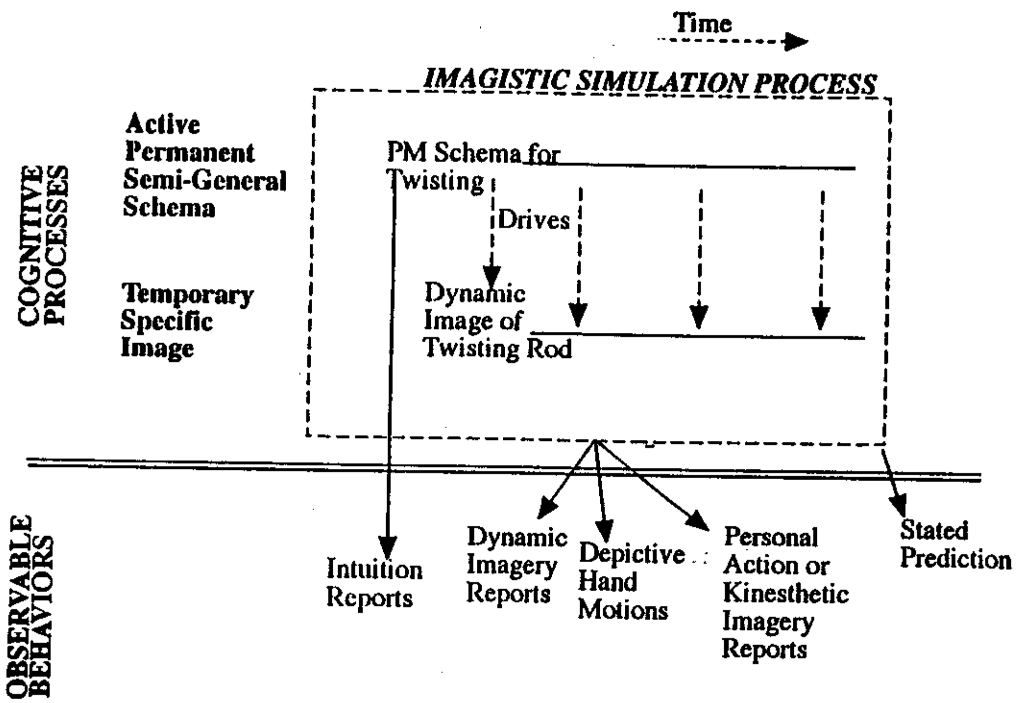
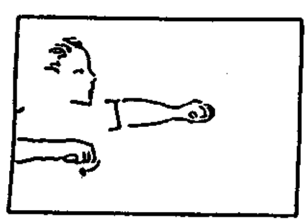


Figure 2 Imagistic simulation process showing hypothesized mental processes producing observable behaviors.



IF I HAVE A LONGER ROD AND I PUT A TWIST ON IT (MOVES HANDS AS IF TWISTING A ROD), IT SEEMS TO ME--AGAIN PHYSICAL INTUITION--THAT IT WILL TWIST MORE... I'M IMAGINING HOLDING SOMETHING LIKE A BAR OF METAL OR SOMETHING LIKE THAT.

Figure 3 Hand movement during imagistic simulation for S2.
Drawing is an exact tracing from photograph of video image.