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Searching an Hypothesis Space When Reasoning About Buoyant Forces: The effect of feedback

Takeshi Okada & David Klahr
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

Abstract

This study addressed the following three questions: (1) To what extent can people's naive, complex, and idiosyncratic knowledge about a real physical domain be captured in a formal representation of an hypothesis space? (2) How does exposure to increasingly complex instances affect subjects' search through the hypothesis space? (3) What is the effect of feedback on hypothesis revision? Six adult subjects solved a series of physics problems involving buoyant forces and liquid displacement. An analysis of subjects' verbal protocols suggests: (1) Naive, complex and idiosyncratic knowledge can characterized by an hypothesis space and changes in that knowledge can then be described as a search through the hypothesis space; (2) People who receive feedback from experimental outcomes change their hypotheses and reach a higher level in the hypothesis space. Mere problem exposure, without feedback, did not lead to hypothesis revision.

Background and Purpose

Questions about the cognitive psychology of scientific discovery have been approached from two relatively distinct perspectives. One approach focuses on the formal, domain-general, processes supporting the cycle of hypothesis induction, evidence generation and hypothesis evaluation. These processes have been characterized as a problem-solving search in a space of hypotheses and a space of experiments (e.g. Dunbar, 1989; Klahr, Dunbar & Fay, 1989; Klahr & Dunbar, 1988; Kuhn, Amsel & O'Loughlin, 1988; Kuhn & Phelps, 1982; Schauble, 1990). All of these process-oriented approaches have used either arbitrary domains or very simple physical domains. The other approach focuses on domain-specific content knowledge about aspects of the physical world (e.g., mass, density, heat, temperature, kinematics, etc.), especially in the area of science education (e.g. Brewer & Samarapungavan, 1990; Chi, Glaser & Rees, 1982; Reif, 1987; Vosniadou & Brewer, 1990). These studies focus on people's content knowledge of the physical world, but they do not articulate the process of hypothesis formation and revision.

This study attempts to integrate the two perspectives by studying people's naive, complex, and idiosyncratic knowledge about a real physical domain, and by representing this knowledge in terms of search through an hypotheses space. Our methodological contribution is a new representation for capturing different levels of knowledge about the physics of buoyant forces. The psychological contribution is a preliminary comparison of the effects of problem exposure plus feedback versus problem exposure alone on people's tendency to revise their hypotheses. If there were a "test effect" from repeated exposure to problems that varied along different physical dimensions, then one would expect to see improvement even in the absence of feedback. In contrast, we found that simply exposing people to a variety of problems, without providing feedback about their predictions was insufficient to cause substantial changes in their hypotheses. Only when feedback was provided did people tend to move toward increasingly correct and consistent hypotheses about the domain under investigation.

Method

Tasks. The basic physical domain involved reasoning about buoyant forces and liquid displacement. Subjects' hypotheses were assessed by a series of pairwise comparisons adapted from work by Itakura et al (1988). (See Figure 1). There were two cubes and two beakers with liquid on a balance scale in all tasks. Subjects were required to predict which side of the scale would go down, or if it would balance, if it were free to move. They were also required to state the reason for their prediction. In Task 1, there is a clay cube in the bottom of the water in the left beaker and a styrofoam cube floating on the water in the right beaker. For Tasks 2 to 10, cubes of the both sides are supported by stiff wire connected with iron stands. Each task contrasts a different set of properties of cubes or liquid (e.g. different volumes, or sizes, or densities, or shapes of cubes, different depths of submersion in liquid, different shape, different densities of liquid).

Design. There were three conditions. In all conditions, subjects were presented with a series of physics problems about which they had to make a prediction based on their understanding of the underlying forces. In the Hypothesis - Feedback (HF) condition, subjects were required to state an hypothesis before receiving feedback on each task. In the Feedback-Hypothesis (FH) condition, subjects were given feedback before being asked to state their current hypothesis. In the Hypothesis - No Feedback (HN) condition, subjects were not given any feedback. In order to analyze the hypothesis space search process in detail, this investigation was designed as a series of related case studies, with two subjects in each condition.

Subjects. Six native Japanese non science graduates of Japanese universities were used. Subjects had not studied Physics since graduating high school. One male and one female were in each condition. The experimenter was a native-speaking Japanese. All experiments were conducted in Japanese.

Procedure. Subjects were run individually. They were instructed in how to give verbal protocols, and all of their task responses were recorded on a VCR and an audio tape recorder. Problems were presented both in a diagram and on a video monitor. Following each prediction, the actual outcome was presented on the monitor (in the HF and FH conditions).

Subjects were told that the ten tasks were related to each other to some extent. The first task had two parts. For the Buoyancy pre-test subjects were asked: "Why do you think the clay sinks, while the styrofoam floats? Please talk aloud about what you are thinking." Following the subject's explanation, the experimenter asked: "On what did you base your explanation?" After the subject's explanation of the basis, the experimenter asked the subject for a confidence rating on a 7 point scale.

The next question was a balance scale question (Task 1: Balance scale pre-test). The experimenter displayed a card with a picture and an information list of the features of this task. Then the experimenter asked the subject to predict which side would go down or if they would balance. The experimenter also asked the subject why he/she thought so. After the subject's prediction and explanation, the experimenter again asked for the subject's basis and confidence level. Cards were displayed so that subjects could refer to them at any time.

Then, task 2 was presented. In the H-F condition and the H-N condition, the subject was asked the same question as in the balance scale pre-test in task 1. Then, each subject in the H-N condition went to the next task. Each subject in the H-F condition was given feedback about the experimental outcome through the display of the videotape and was asked to state (a) a reason why he/she thought this result occurred, (b) the basis of his/her explanation, and the confidence in that explanation. In the F-H condition, subjects were not asked to predict the outcome. Instead, they were first shown feedback on the experimental outcome and then asked to give a reason for the outcome, the basis of the explanation, and the confidence level.

The same procedure continued through task 10, after which subjects were asked if they could state a consistent theory that could account for all the tasks. Subjects were also asked to state the basis of their explanation and their confidence in it. Subjects were asked to sort these ten tasks based on the similarity of the underlying physical principle determining their outcomes. Then they were asked to subdivide each category, and finally to combine the first category to a higher group if possible.

Then subjects were asked the original buoyancy question and the balance scale question in task 1 again (Buoyancy post-test and Balance scale post-test). Finally, each subject was asked about his/her background knowledge about physics and science.

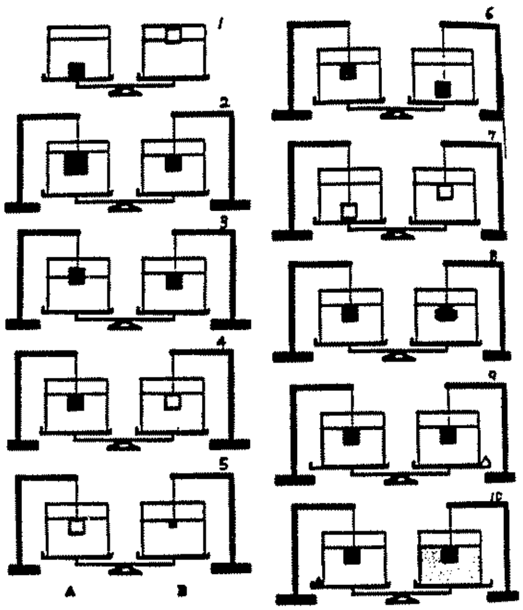

Figure 1. Tasks in this experiment.

Results

Coding of hypotheses. Subjects' protocols were transcribed from tapes and coded at a high enough level to describe the subjects' hypotheses. The coding categories are shown in Table 1 and the hypothesis space is described as a hierarchical tree structure (See Figures 3, 5, 7 and 9, which depict individual subjects' movement through the hypothesis space). Each node in the hypothesis space represents a rule about how to determine the net force on each side of the scale. The top node shows three types of "Expert Physicist" theories.

1) <u>Tension theory:</u> F=Wc+Wl+Wb-T. In this case, external force is the force on the container and the water and the block.
2) <u>Buoyancy theory:</u> F=Wc+Wl+Dl*Vb.l*g. Dl*Vb.l*g means buoyancy force, which is determined by the density of the liquid, the volume of displaced liquid (which is equal to the volume of the block in the water) and the gravitational constant. In this case, external force is the force on the container and the block.
3) <u>Hydrostatic Pressure theory:</u> F=Dl*Hl*A*g. In this case, external force is the force on the container.

The hypothesis space is divided into three frames derived from the expert theories: the Tension frame in the left (which includes the Tension Hypotheses group), the Buoyancy frame in the middle (which includes the Buoyancy Hypotheses group), and the Hydrostatic Pressure frame in the right (which includes the Hydrostatic Pressure Hypotheses group). Because there is insufficient information about the tension force, the Tension theory can not predict the right answers. The SAME BLOCK hypothesis does not belong to these three frames, because it is more basic than them.

There are sub-categories in each frame. Levels are loosely connected to the vertical dimension. Hypotheses depicted near the top of Figure 3 can be regarded as being closer to the Expert solutions. The nested boxes within a larger box can be regarded as in the same level. Solid lines between nodes mean that there is a direct relationship and dashed lines mean that there is an indirect relationship.

Table 1 Coding Categories of Protocol

T ^ Wb (F x; Wb) The tension from the wire supports the weight of the block and the scale force is unrelated to the weight of the block.
F : Wb-T The scale force is determined by the weight of the block minus the tension force.
F=Wc+Wl+Wb-T (Tension theory). The scale force equals the sum of the container weight plus the liquid weight plus the block weight minus the tension from the wire. This is a physicist theory.
F : Sb The scale force is determined by the size of the block.
F : Sb.l The scale force is determined by the size of the block in the liquid.
F : Wb The scale force is determined by the weight of the block.
F : Wb.l The scale force is determined by the weight of the block in the liquid.
F : SAb The scale force is determined by the surface area of the block.
F : SAb.l The scale force is determined by the surface area of the block in the liquid.
F : VSAb The scale force is determined by the volume (which is related to the surface area) of the block.
F : VSAb.l The scale force is determined by the volume (which is related to the surface area) of the block in the liquid.
F : Vb The scale force is determined by the volume of the block.
F : Vb.l The scale force is determined by the volume of the block in the liquid.
F : Dl,,Vb.l (= F : SGl,,Vb.l) The scale force is determined by the density of the liquid and the volume of the block in the liquid. In this case, subject may not know the clear relationship between the density of the liquid and the volume of the block in the liquid (that is, the density of liquid times the volume of the block in the liquid determines the scale force).
F : Dl*Vb.l (= F : SGl*Vb.l) The scale force is determined by the density of the liquid times the volume of the block in the liquid.
F=Wc+Wl+Dl*Vb.l*g (Buoyancy theory). The scale force equals to the weight of the container plus the weight of the liquid plus the density of the liquid times the volume of the block in the liquid times the gravitation force. Dl*Vb.l means the buoyancy force.
F : Hl The scale force is determined by the height of the liquid.
F : Dl,,Hl (= F : SGl,,Hl) The scale force is determined by the density of the liquid and the height of the liquid. In this case, subject may not know the clear relationship between the density of the liquid and the height of the liquid (that is, the density of the liquid times the height of the liquid determines the scale force).
F : Dl*Hl (= F : SGl*Hl) The scale force is determined by the density of the liquid times the height of the liquid.
F=Wc+Dl*Hl*A*g (Hydrostatic pressure theory). The scale force equals the weight of the container plus the density of the liquid times the height of the liquid times the bottom area times gravitation force.
SAME BLOCK If the same sort of blocks are put on the both sides of a balance scale, the scale balances. This is a basic idea about balance scale.
NO IDEA The subject did not have any clear idea about the task

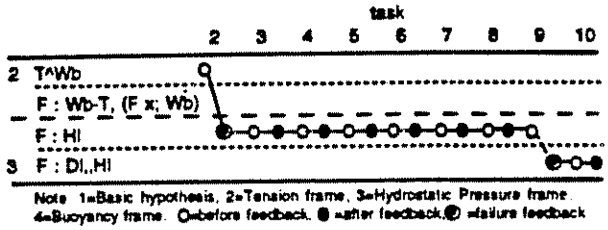

Figure 2. Hypotheses change following each task for S1.

Individual subjects

We will describe in detail only four subjects. Space constraints preclude a description of the other two. Each subject's search through the hypothesis space is depicted in two ways. The tabular form (Figures 2, 4 and 6) shows the temporal dynamics of each problem and the effect of feedback (if any). In these Figures, a plain line between dots means that the subject changed hypotheses without keeping previous hypothesis for previous tasks. Dashed lines between dots mean that subjects searched for new hypotheses while maintaining a previous hypothesis for previous tasks. In addition to the temporal representation, we use the hierarchical representation of the hypotheses space shown in Figures 3, 5 and 7. In these figures, plain lines with arrows mean that the subject changed hypotheses without keeping the previous hypothesis. Dashed lines with an arrow mean that the subject searched for a new hypothesis while keeping a previous hypothesis.

H-F condition, S1 (male). S1's pre-test results showed that he had basic knowledge about buoyancy and balance scales. S1 changed his hypothesis twice; after failure feedback in task 2 and task 9. (See Figure 2) Failure feedback was a key factor in his theory revision. His confidence rating was also changed from 7 to 3 after the first failure feedback and 5 to 3 after the second failure feedback. Figure 3 shows the change of hypotheses through each task. S1 moved from the Tension frame to the Hydrostatic Pressure frame in the first change and moved from lower level to higher level in the Hydrostatic Pressure frame in the second change. For his final "integrative" theory, S1 actually maintained two distinct theories - one to account for Tasks 2-8, and another for 9 and 10.

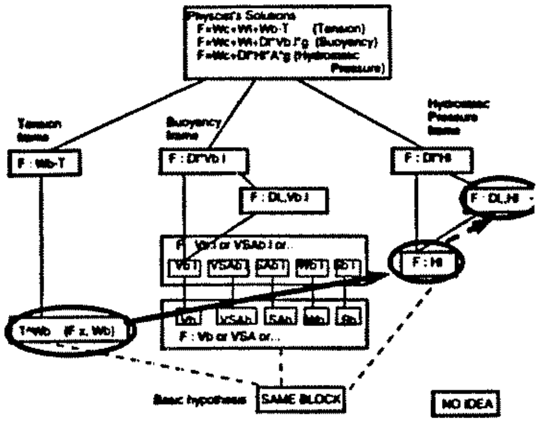

Figure 3. The Hypothesis Space Trajectory for S1.

H-F condition, S2 (female). S2 incorrectly answered the buoyancy pre-tests using only the concept of weight. She did have basic knowledge about balance scales. S2 changed her hypotheses seven times; (See Figures 4 and 5) after failure feedback in task 3, before receiving feedback and after failure feedback in task 4, before receiving feedback and after failure feedback in task 8, and before receiving failure feedback and after failure feedback in task 9. She changed from a lower level of hypothesis to a higher level of hypothesis in task 3. She changed from a less correct hypothesis to a more correct hypothesis in task 4 and task 8. However, in task 9, S2 could not find any hypothesis at all because she lacked a clear idea about liquid density. Although she also changed her hypotheses when she faced new tasks before receiving failure feedback, the changes were small or in the direction from a higher level to a lower level. That is, she changed from the concept of size in which the concept of weight and volume are not distinguished in task 3 to the concept of weight which became distinguished from the concept of volume.

The change from V to VSA in task 8 can also be regarded as a small change. In this case, S2 did not attend to the relationship between volume and surface area before being faced with task 8. On task 8, her knowledge about that relationship was activated from her memory as she stated in her basis. The change from V in task 8 to SAME BLOCK in task 9 can be regarded as a change of application of her existing hypothesis to the new task rather than a discovery of a new hypothesis, because SAME BLOCK hypothesis is regarded as a basic hypothesis that even children have. It is clear that S2 moved from a lower level to a higher level and moved from a less correct hypotheses to a more correct hypotheses in the Buoyancy frame. When she was faced with task 9, she applied a basic hypothesis. However, she could not interpret last two tasks. S2 had three types of final hypotheses which applied to different tasks. Although the first two hypotheses were in the same category, she was unable to integrate them into a unified hypothesis at the higher level.

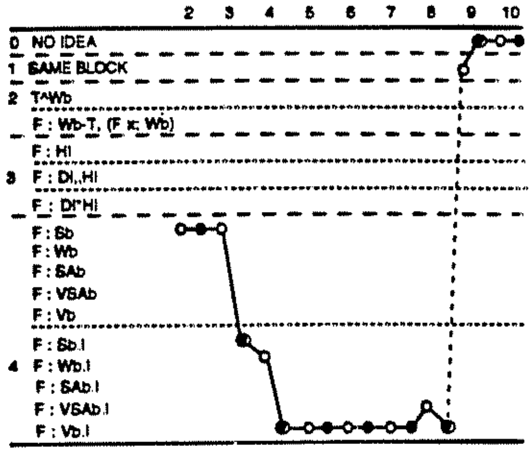

Figure 4. Hypotheses change following each task for S2.

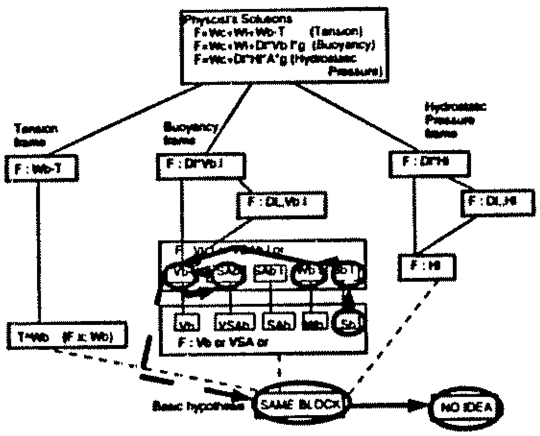

Figure 5. Hypothesis Space Trajectory for S2.

F-H condition, S3 (male). S3 had basic knowledge about buoyancy and balance scales. He changed his hypothesis twice; in task 2 and in task 9. (Figures 6 and 7) Although subjects in the F-H condition were not required to state their hypotheses before receiving feedback, we infer their implicit prediction from their hypothesis on the previous task. Thus, we infer that S3 received failure feedback in task 2 and task 9. In task 2, he asked, "While the wire supports blocks, the left side went down?" Our inference is that he had T^Wb hypothesis and had predicted that the scale should have balanced, but it didn't. In task 9, because his hypothesis in task 8 predicts the wrong outcome, we also infer that he received failure feedback. In that sense, failure feedback influenced him to change his hypotheses. Figures 6 and 7 show that he moved from the Tension frame to the Buoyancy frame in the first change and moved from a lower level to a higher level in this frame in the second change. He had a single hypothesis to explain tasks 2-10.

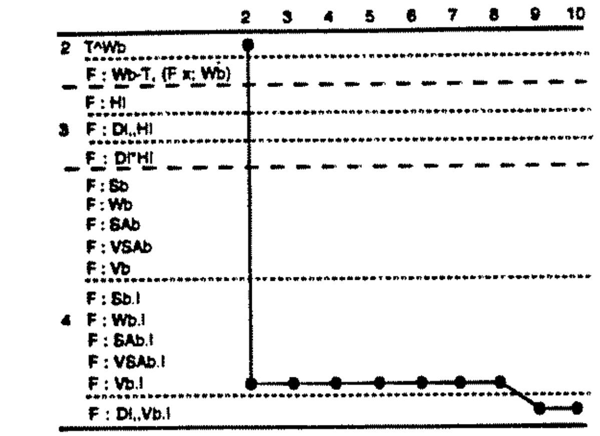

Figure 6. Hypotheses change following each task for S3.

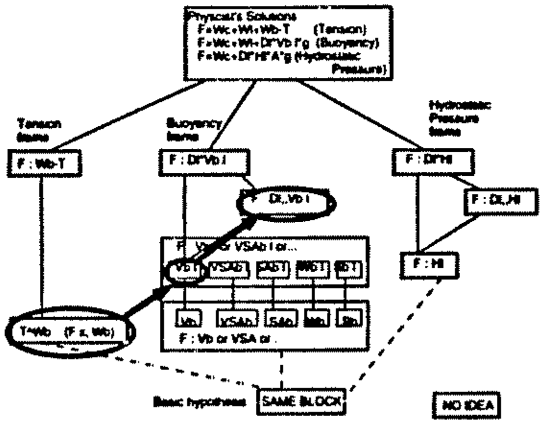

Figure 7. Hypothesis Space Trajectory for S3.

H-N condition, S4 (female). S4 had basic knowledge about buoyancy and balance scales. S4 did not change her hypotheses at all, although she stated a different hypotheses vaguely at the same time in task 6 and 7. She remained in the Tension frame throughout. She had one hypothesis to account for all tasks.

Summary of Findings

1) People's knowledge about physical domains can be characterized as an hypothesis space, and changes in that knowledge can be described as a search through the hypothesis space.

2) There was a dramatic difference between the H-F condition and the H-N condition. Subjects who received feedback changed their hypotheses from a frame to another frame or from a lower level to a higher level, especially after receiving failure feedback. On the other hand, subjects who did not receive feedback did not change their hypotheses. That is, simply being exposed to a variety of problems was insufficient to make subjects search the hypothesis space. However, in the H-F condition (S1, S2), subjects did make small changes in their hypotheses even when they faced new tasks before receiving feedback.

3) There is no clear difference between the H-F condition and the F-H condition.

4) Subjects in the feedback conditions used feedback information from earlier tasks to solve subsequent tasks. However, subject's explanations did not necessarily generalize to all tasks. Instead, they used several different explanations for different groups of tasks.

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