Epistemic Actions in Science Education

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Abstract. Epistemic actions are actions in the physical environment taken with the intent of gathering information or facilitating cognition. As students and geologists explain how they integrated observations from artificial rock outcrops to select the best model of a three-dimensional geological structure, they occasionally take the following actions, which we interpret as epistemic: remove rejected models from the field of view, juxtapose two candidate models, juxtapose and align a candidate model with their sketch map, rotate a candidate model into alignment with the full scale geological structure, and reorder their field notes from a sentential order into a spatial configuration. Our study differs from prior work on epistemic actions in that our participants manipulate spatial representations (models, sketches, maps), rather than non-representational objects. When epistemic actions are applied to representations, the actions can exploit the dual nature of representations by manipulating the physical aspect to enhance the representational aspect.

Keywords: spatial cognition, epistemic actions, science education

1 Introduction

Kirsch and Maglio [1] introduced the term "epistemic action" to designate actions which humans (or other agents) take to alter their physical environment with the intent of gathering information and facilitating cognition.[1] Epistemic actions may uncover information that is hidden, or reduce the memory required in mental computation, or reduce the number of steps involved in mental computation, or reduce the probability of error in mental computation. Epistemic actions change the informa-

[1] Magnani [24] used a similar term, "epistemic acting," more broadly, to encompass all actions that provide the actor with additional knowledge and information, including actions that do not alter anything in the environment (e.g., "looking [from different viewpoints]," "checking," "evaluating," "feeling [a piece of cloth]".) Roth [25] (p. 142) used "epistemic action" to refer to sensing of objects and "ergotic action" to refer to manipulating objects in a school laboratory setting. In this paper, we use the term "epistemic action" in the original sense of Kirsh and Maglio.

tional state of the actor, as well as the physical state of the environment. Kirsch and Maglio contrasted epistemic actions with "pragmatic actions," those taken to implement a plan, or implement a reaction, or in some other way move oneself closer to a goal.

Kirsch and Maglio [1] explicated their ideas in terms of the computer game Tetris. They showed that expert players make frequent moves that do not advance the goal of nestling polygons together into space-conserving configurations, but do gain information. For example, a player might slide a falling polygon over to contact the side of the screen and then count columns outwards from the side to determine where to drop the polygon down to fit into a target slot. For a skilled player this backtracking maneuver is more time-efficient than waiting for the polygon to fall low enough for the judgment to be made by direct visual inspection. At a different point in the game, a player might rotate a polygon through all four of the available configurations before selecting a configuration. Kirsh and Maglio showed that such physical rotation, followed by direction perceptual comparison of the polygon and the available target slots, is more time-efficient than the corresponding mental rotation. As an individual player's skill increases from novice to expert, the frequency of such "extraneous" moves increases [2].

In this paper, we apply the concept of epistemic actions to science and science education. Scientists and science students manipulate objects in the physical world in the course of trying to solve cognitively demanding puzzles. We argue that epistemic actions, in the sense of Kirsch and Maglio [1], are an underappreciated tool that scientists use, and that science students could be taught to use, to enhance the efficiency of their cognitive effort. We begin by showing examples of participant actions that we believe to be epistemic which emerged in our own study of spatial thinking in geosciences. We then describe epistemic actions in other domains of science education, and conclude by offering some generalizations and hypotheses about how epistemic actions may work.

2 Epistemic Actions in our Geoscience Field Study

Our study [3] investigates how students and professional geologists gather and record spatial information from rock outcrops scattered across a large field area, and then integrate that information to form a mental model of a geological structure, keeping in mind that the structure is partly eroded and mostly buried. Participants observe and take notes on eight artificial outcrops constructed on a campus, then select from an array of fourteen 3-D scale models to indicate which they think could represent the shape of a structure formed by the layered rocks in the eight outcrops. The scale models vary systematically on key attributes, including convex/concave, circular/elongate, symmetric/asymmetric, open/closed, and shallow/deep. Participants are videotaped as they make their selection and explain why they chose the selected model and rejected the other models. Based on their comments and body language, students find this task difficult but engaging, and all appear to be trying determinedly to solve the puzzle posed to the best of their ability.

As detailed elsewhere [4], students use abundant deictic (pointing) gestures to indicate features on their notes, a model or group of models, a real-world direction, or the outcrops in that real-world direction. For example, a student points over his shoulder to indicate the location of the most steeply-dipping outcrops. They also make frequent use of iconic gestures, while discussing or describing attributes of an observed outcrop, a specific model, a group of models, or a hypothesized structure. For example, a student uses a cupped hand to convey her interpretation that the structure is concave upwards.

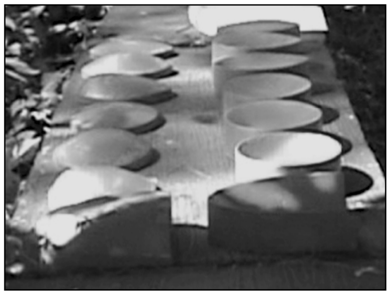
In addition to abundant deictic and iconic gestures, the videotapes also document instances in which participants spontaneously move their hands in ways that do not have apparent communicative value, manipulating the objects available to them in a manner that we interpret as "epistemic actions."

2.1 Situation #1: Participant Moves Rejected Models Out of View

Participants frequently begin their reasoning process by eliminating individual models or categories of models, for example, all the convex models. In many cases, they merely point out the rejected models with deictic gesture, or describe the rejected category in words (i.e., "it can't be convex"). But in some cases, they go to considerable effort to remove the rejected models from their field of view, for example by setting them off to the side (Fig. 1), or handing them to the experimenter. We infer that they are seeking to decrease their perceptual and cognitive load by decreasing the complexity of the visual array and by reducing the number of possibilities that are actively competing for their attention. These actions serve to address one of the basic problems of visual attention, namely that there is a limited capacity for processing information. Although there is a considerable research literature showing that humans are able to focus attention on some rather than other stimuli within a particular visual array [5], at least some processing is necessary when there are competing stimuli, and thus any actions that reduce that competition may be expected to simplify the task [6].

2.2 Situation #2: Participant Moves Two Candidate Models Side by Side

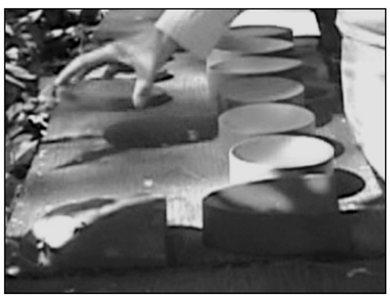
As participants progress through their reasoning process, they may take two candidate models out of the array and place them side by side (Fig. 2.) We infer that this action is intended to facilitate comparing and contrasting attributes of the two models. The side-by-side comparison technique is employed when the two models differ subtly; for example, in Fig. 2 the two models are both concave, both elongate, both steep-sided, both closed, and differ only in that one is symmetrical along the long axis while the other is asymmetrical. Based on eye movements of people who were asked to recreate spatial patterns of colored blocks working from a visually-available model, Ballard, Hayhoe, Pook and Rao [7] concluded that their participants adopted a "minimum memory strategy" when the model and under-construction area were close together. They kept in mind only one small element of the model (for example, the color of the next block), and relied on repeated revisits back and forth between the



Time: 00:01
{Participant looks at the array of fourteen models.}

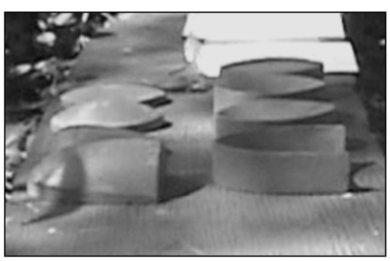
Time: 00:05
{Participant picks up circular steeply-sloping asymmetric convex model and places it to the side, away from the array of models.} **I don't think it** [structure] **is round.**

Time: 00:06
{Action repeated for circular steeply-sloping symmetric convex model.}



Time: 00:09
{Participant picks circular shallowly-sloping symmetric convex model and places it to the side of the array.}

Time: 00:12-00:17
{Action repeated for three other circular models.}



Time: 00:22
{Participant repositions remaining models, all elongate, into a tight grouping.}

Note: Times are minutes:seconds since experimenter asked participant to choose model.

Fig. 1. Participant places rejected models out of field of view. We infer that the purpose of this action is to decrease the number of visually-available comparisons.

model and the under-construction block array. The revisits allowed them to acquire information incrementally and avoid even modest demands on visual memory. Ballard, et al.'s participants overwhelmingly favored this minimal memory strategy even though it was more time-consuming than remembering multiple aspects of the model, and even though they were instructed to complete the task as quickly as possible. When Ballard, et al. increased the distance between model and copy, use of the minimal memory strategy decreased.

We hypothesize that by moving two subtly-different models side-by-side, our participants enabled a minimal memory strategy to efficiently compare and contrast attributes of the models incrementally, without relying on visual memory to carry the entire model shape as attention is transferred from model to model.

Time: 02:37

Right here *{touches deep point of asymmetric model}* **and right here** *{touches deep point of symmetric model}*, **this hole here** *{touches deepest point of asymmetric model}* **is much deeper than here** *{touches deepest point of symmetric model}*.

Fig. 2. After rejecting most models, this participant took the remaining two candidate models out of the array and placed them side-by-side, to faciliate comparison of details.

2.3 Situation #3: Participant Moves Candidate Model Adjacent to Inscriptions

In some cases, participants place a candidate 3-D model side by side with their inscriptions (field notes) (Fig. 3). We infer that this juxtaposition facilitates the process of comparing observation (in the notes) with interpretation (embodied in the candidate 3-D model), presumably through enabling the minimal memory strategy as described above. Participants' inscriptions took many forms [3], including a map of the field area with outcrop locations marked. Among the participants who had a map, we noted an additional epistemic action: participants rotated the map and candidate model such that the long axis of the model was oriented parallel to the long axis of the cluster of outcrop positions marked on the map (Fig. 3). This alignment allowed a direct perceptual comparison of inscriptions and model, without requiring the additional cognitive load of mental rotation, as in the case of Kirsh and Maglio's [1] Tetris players.

2.4 Situation #4: Participant Rotates Model to Align with the Referent Space

In a few cases, a participant spontaneously rotated a model or models to align with the full-scale structure formed by the outcrops in the perceptual space[2] (Fig. 4). As in

[2] After completing their explanation of their model selection, all participants were asked by the experimenter to rotate their selected model into alignment with the full-scale structure. In this

Situation #3, we hypothesize that the alignment achieved by physical rotation enabled a direct comparison, eliminating the cognitive load of mental rotation. An interesting aspect of Situation #4 is that the full-scale structure was not perceptually available to compare with the model structure. Only 2 of the 8 outcrops were visible to the participants as they made and defended their model selection. We hypothesize that as they moved through the field area from outcrop to outcrop and then back to the starting place, some participants acquired or constructed an embodied knowledge of the outcrop locations and configuration, and that embodied knowledge is somehow anchored to, or superimposed upon the landscape through which they moved.

Time: 03:47
{With pencil in right hand points to the spot on the map where she has recorded outcrop #1. With her left thumb touches a point on the model that she thinks may be analogous…. Action repeated for outcrops 2 and 3.}

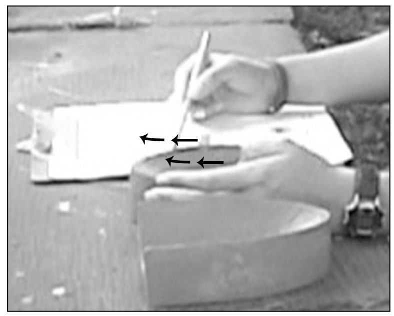


Fig. 3. This participant has placed her inscriptions (notes) side by side with a candidate model to facilitate comparison between her recorded observations and her candidate interpretation.

2.5 Situation #5: Participant Rips Up Inscriptions, and Reorders Them in Space

In the no-map condition of our experiment [3], participants recorded their observations onto blank paper. Some participants situated their observations spatially to form a sketch map of the field area, and others recorded their observations "sententially" [8], in chronological order on the page from top to bottom, left to right, like text in a book. One participant, a novice to field geology, recorded her observations sententially, sketching each outcrop as she visited it. Then, when she was confronted with the selection task, she spontaneously tore up her papers so that each outcrop sketch was on a separate scrap of paper, and arranged the scraps spatially into a rough plan view of the outcrop locations (Fig. 5).

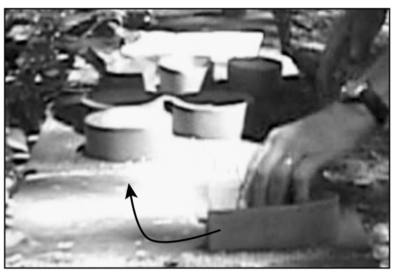
paper, we are referring to individuals who spontaneously elected to align their model with the structure before being asked to do so by the experimenter.

Time: 00:50- 01:06
{Participant rejects the convex models as a group, and experimenter removes them.}

Time: 01:37
Based on my inferences *{looks at map}* **you know** *{looks east, towards last few outcrops visited}* **if I were to orient it** [model]…

Time: 01:40
{Rotates elongate shallowly-dipping symmetric model approximately 80° clockwise, to align with the full-scale structure formed by the outcrops.}

Time: 01:41-01:48
{Repeats action for five other models.} **…relative to north, south, east, and west…**



Time: 01:49
…they [models] **would be something like** *{Begins to rotate elongate open-ended steeply-sloping asymmetric model clockwise}*

Time: 01:49
…this. *{Completes rotation; model is now in alignment with full-scale structure.}*

{Adjusts all models so that they are aligned with the full-scale structure of the referent space.}

Time: 01:55
And so now I have to choose which of these [model] **possibilities is correct…**

Fig. 4. This participant, an expert, rotates several candidate models so that the long axis of the model aligns with the long axis of the full-scale structure.

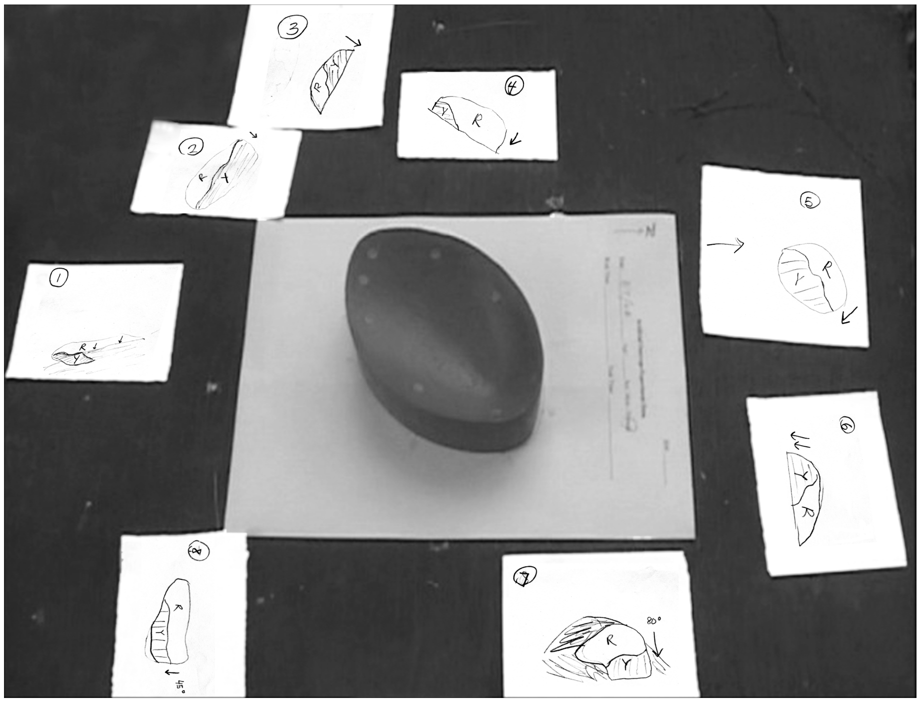


Fig. 5. While observing the eight outcrops, this participant recorded observations onto blank sheets of paper "sententially," that is, sequenced from top to bottom, left to right on the paper, like text in a book. When confronted with the integrative task, she tore up her inscriptions into small rectangles with one outcrop per rectangle, and reorganized them into a map-like spatial arrangement. (Note: in order to show the reader both the spatial arrangement of the paper scraps and the details of the sketch, this figure was constructed by scanning the student's inscriptions and superimposing the scanned sketches onto a video screen shot).

3 Other Occurrences of Epistemic Actions in Science Education

In the laboratory or "hands-on" component of a well-taught science education program, students are engaged in manipulating physical objects while thinking hard—conditions that may tend to foster use of epistemic actions. And indeed, we can envision epistemic actions across a range of science fields. For example:

- Elementary school children grow bean plants in paper cups. They place their bean plants in a row along the window sill such that each plant gets the same amount of sunlight. Each child waters his or her bean plant by a different amount each day. Initially, they arrange the plants in alphabetical order by child's name. Then, as the plants sprout and begin to grow, they rearrange the bean plants in order by amount of daily watering, to make it easier to see the relationship between amount of water and growth rate.

- High school chemistry students arrange their test tubes in a test tube rack in order so that the tube that received the most reagent is farthest to the right.
- College paleontology students begin their study of a new taxonomic group by arranging fossils across the lab table in stratigraphic order from oldest to youngest, to make it easier to detect evolutionary trends in fossil morphology.
- Earth Science students begin their study of igneous rocks by sorting a pile of hand samples into a coarse-grained cluster and a fine-grained grained cluster, to reinforce the conceptual distinction between intrusive rocks (which cooled slowly within the Earth's crust and thus have large crystals) and extrusive rocks (which cooled quickly at the Earth's surface and thus have small crystals).
- Elementary school geography students, or high school Earth Science students, rotate the map of their surroundings until map and referent are aligned. This makes it easier to see the representational and configurational correspondences between map and referent space, without the effort of mental rotation, which is known to be a cognitively demanding task [9].

4 Discussion

4.1 Are Epistemic Actions Consciously Purposeful?

The participants in our study produced the actions described above spontaneously, as they struggled to puzzle their way through a spatially-demanding task that most found difficult. Some participants first asked whether it was OK to move or turn the models, which suggests that they knew in advance that such actions would be beneficial. They valued these actions sufficiently that they were willing to risk rejection of a potentially forbidden move, and they anticipated that the experimenter might see these actions as being of sufficient value to outlaw.

4.2 Are Epistemic Actions Always Spatial?

All of the examples of epistemic actions we have provided thus far, and the original Tetris examples of Kirsch and Maglio [1], have involved spatial thinking, that is, thinking that finds meaning in the shape, size, orientation, location, direction, or trajectory of objects, processes, or phenomena, or the relative positions in space of multiple objects, processes, or phenomena. Spatial examples of epistemic actions seem most obvious and most powerful. But is this association between epistemic actions and spatial thinking inevitable? Are *all* epistemic actions in service of spatial thinking?

No. It is possible to think of counter-examples of epistemic actions that seek non-spatial information. An everyday example would be placing two paint chips side by side to make it easier to determine which is darker or more reddish, seeking information about *color*. The science equivalent would be placing a spatula full of dirt or sediment next to the color chips in the Munsell color chart [11].

4.3 Taxonomies of Epistemic Actions

Kirsh [12] developed a classification scheme for how humans (or other intelligent agents) can manage their spatial environment: (a) spatial arrangements that simplify choice; (b) spatial arrangements that simplify perception, and (c) spatial dynamics that simplify internal computation. Our Situation #1, in which participants remove rejected 3-D models from view, is a spatial arrangement that simplifies choice. Situation #2 and #3, in which participants juxtapose two items to simplify comparison, are spatial arrangements that simplify perception. Situations #3 and #4 from the outcrop experiment, plus the case of rotating a map to align with the terrain, simplify internal computation by eliminating the need for mental rotation.

Kirsh's scheme classified epistemic actions according to the change in cognitive or informational state of the actor. Epistemic actions could also be classified by the nature of the change to the environment: (a) relocate/remove/hide objects, (b) cluster objects, (c) juxtapose objects, (d) order or array objects, (e) rotate/reorient objects. Considering both classification schemes together yields a two-dimensional matrix for categorizing epistemic actions (Table 1). Each cell in the matrix of Table 1 describes benefits obtained by the specified change to the environment (row) and change to the cognitive state of the actor (column).

Table 1. Two-dimensional taxonomy of epistemic actions

	Changes to cognitive state of actor (after Kirsh)		
Change to environment	*Simplify choice*	*Simplify perception*	*Simplify cognition*
Remove or hide object(s)	Fewer apparent choices	Less visual input, fewer visual distractions	Fewer pairwise comparisons required
Cluster objects	Choice is among few clusters (e.g., concave vs. convex) rather than among many individuals	Easier to see within-group similarities; easier to see between-group differences	Fewer attributes that need to be considered
Juxtapose objects		Easier to see differences and similarities	Less demand on visual memory
Order or array objects	Easier to select end members (e.g., largest, smallest) or central "typical" example	Easier to see trends (e.g., bean plant growth by watering rate) and correlations	No need for mental re-ordering
Rotate/ reorient objects		Easier to see correspondences	No need for mental rotation

"Juxtapose objects" appears at first glance to be a special case of "cluster objects," but we have separated them because the information gained and the nature of the change of cognitive state may be different. The value-added of juxtaposing two similar objects is that it is easier to perceive similarities and differences, without the cognitive load of carrying a detailed image of object 1 in visual memory while the gaze is shifted laterally to object 2 [7]. The value-added of clustering objects into groups is that one can then reason about a small number of groups rather than a larger number of individual objects. An example of the latter would be separating the trilobites from the brachiopods in a pile of fossils; an example of the former would be juxtaposing two individual trilobite samples to compare their spines.

The taxonomy of Table 1 has been structured to accommodate a variety of tasks and to allow extension as new observations accrue from other studies.

4.4 Epistemic Actions and the Duality Principle of Representations

Kirsh's [12] taxonomy of actions to manage space was based on observation of people playing games and engaging in everyday activities such as cooking, assembling furniture, and bagging groceries. In the case of science or science education, we suggest that epistemic actions can enhance cognition in a manner not explored by Kirsh: epistemic actions can exploit or enhance the dual nature of representations.

A spatial representation, such as a map, graph, or 3-D scale model, has a dual nature: it is, simultaneously, a concrete, physical object, and a symbol that represents something other than itself [13-18]. We suggest three ways in which epistemic actions can exploit or enhance the dual nature of representations:

1. The action can rearrange or reorder the physical aspect of the representation so that the referential aspect of the representation is more salient and/or has more dimensions.
2. The action can rearrange or reorder the physical aspect of the materials so that a more useful representation replaces a less useful representation.
3. The action can create a dual-natured representation from what had previously been mere non-representational objects.

Mechanism (1): Manipulate the Physical Representation to Enhance or Foreground its Referential Meaning. In Situation #4 of the artificial outcrop experiment, an expert rotates candidate 3-D scale models to align with the full-scale structure. Before rotation, the correct model accurately represented the full-scale structure with respect to the attributes of concave/convex, elongate/circular, steep-sided/gentle-sided, symmetric/asymmetric, and closed/open. After rotation, the model accurately represented the full-scale structure with respect to all of those attributes, and also with respect to alignment of the long axis. In other words, manipulating the physical object transformed the representation into a more complete or more perfect analogy to the referent structure. The same is true of rotating a map to align with the represented terrain [19].

In addition to creating a new correspondence (alignment) where none had existed previously, rotating the correct model to align with the referent space makes the other correspondences more salient, and easier to check or verify. On the other hand, if the model chosen is an incorrect model (for example, open-ended rather than closed-contoured), the discrepancy between model and full-scale structure becomes harder to overlook when the long axes of the model and referent are brought into alignment.

Mechanism (2): Manipulate the Physical Representation to Create a More Useful Representation. In Situation #5 of the artificial outcrop experiment, the participant had initially arranged annotated sketches of each outcrop onto her paper such that the down-paper dimension represented the temporal sequence in which the eight outcrops had been visited and the observations had been made. Upon receiving the task directions and seeing the choice array, she apparently realized that this was not a useful organizational strategy. She physically destroyed that organization schema. Then she physically reorganized the fragments into a more task-relevant spatial arrangement, in which positions of outcrop sketches represented positions of full-scale outcrops. This participant apparently had the ability to think of her inscriptions as both (a) a concrete object that could be torn into pieces and reordered, and (b) a set of symbolic marks standing for individual outcrops.

Mechanism (3): Manipulate the Physical World to Carry Representational Meaning. In several of the examples described above, the objects have no representational significance before the epistemic action. The epistemic action creates representational significance where none had previously existed.

For example, in the case of the children's growing bean plants, as a consequence of the epistemic action, the spatial dimension parallel to the window sill becomes a representation of water per unit time. The vertical dimension, the height of each plant, becomes a representation of growth rate as a function of watering rate. The entire array of plants becomes a living bar graph.

In the case of the fossils arranged on the table, the spatial dimension along the line of fossils acquires two representational aspects, which run in parallel: geologic time and evolutionary distance.

In the case of the igneous rocks, the two piles of rocks, fine-grained and coarse-grained, represent the fundamental division of igneous rocks into extrusive and intrusive products of cooling magma. Within each pile, the rocks could further be ordered according to the percentage of light-colored minerals, an indicator of silica content.

Kirlik [20] presents a compelling non-science example, in which a skilled short-order cook continuously manipulates the positions of steaks on a grill, such that the near-far axis of the grill (from the cook's perspective) represents doneness requested by the customer, and the distance from left-hand edge of the grill represents time remaining until desired doneness. This skilled cook need only monitor the perceptually-available attribute of distance from the left edge of grill, and need not try to perceive the hidden attribute of interior pinkness, nor try to remember the variable attribute of elapsed-duration-on-grill. A less skilled cook in the same diner created only one axis of representation (the near-far requested-doneness axis), and the least skilled cook had no representations at all, only steaks.

5 Conclusions & Directions for Further Research

Cowley and MacDorman [21] make the case that capability and tendency to use epistemic actions is an attribute that separates humans from other primates and from androids. If so, then we might expect that the most cognitively demanding of human enterprises, including science, would make use of this capability.

In reflecting on the significance of their work, Maglio and Kirsh [2] note (p. 396) that "it is no surprise…that people offload symbolic computation (e.g., preferring paper and pencil to mental arithmetic…), but it is a surprise to discover that people offload perceptual computation as well." This description applies well to science education. Science and math educators have long recognized the power of "offloading symbolic computation," and explicitly teach the techniques of creating and manipulating equations, graphs, tables, concept maps, and other symbolic representations. However, science educators have generally not recognized or emphasized that humans can also "set up their external environment to facilitate perceptual processing" (p. 396).

All science reform efforts emphasize that students should have ample opportunities for "hands-on" inquiry [22]. But we are just beginning to understand what students should *do* with those hands in order to make connections between the physical objects available in the laboratory or field-learning environment and the representations and concepts that lie at the heart of science. We hypothesize that epistemic actions may be a valuable laboratory inquiry strategy that could be fostered through instruction and investigated through research.

Questions for future research include the following: Can instructors foster epistemic actions in their students? If so, do student learning outcomes on laboratory activities improve? Is there individual variation in the epistemic actions found useful by different science students or scientists, as Schwan and Riempp [23] have found during instruction on how to tie nautical knots? Do those scientists who have reputations for "good hands in the lab" make more epistemic actions than those who do not, by analogy with the strategic management of one's surrounding space that Kirsh [12] found to be an attribute of expertise in practical domains?

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