The Distribution of Representation

Lisa M. Osbeck

University of West Georgia

Nancy J. Nersessian

Georgia Institute of Technology

Abstract

Recent cognitive science frameworks depicting cognitive processing as 'distributed' across persons and environments require new ways of conceptualizing representation. That is, if representation is to be retained as an explanatory concept, it must foreground the interactive participation of persons and of different representational formats, rather than remain an internal *or* external phenomenon. This paper is directed towards such an account. It draws upon findings in a wide-scale, multi-year study investigating cognitive practices of research scientists in two university research laboratories. The research is guided by the assumption that cognitive practices generally and science practices specifically comprise a complex system of persons, devices, artifacts, instruments, texts, and traditions. We use an interdisciplinary methodological approach that combines ethnographic observations and analyses with cognitive-historical analysis. Here we present two interrelated interpretive notions emerging from our analysis that have particular relevance to the project of providing an account of representation compatible with the assumption that cognitive processing is distributed.

Keywords: representation, distributed cognition, model-based reasoning, ethnographic methods, practices

Introduction

'Representation', like 'idea' before it, is one of the most ambiguous and multifarious concepts in the history of philosophy. Yet it is frequently treated as monolithic when subjected to debate. The foundational claim of cognitive science that an intelligent system's computations take place over representations has made the very term 'representation' anathema for many theorists who prioritize human practice, discourse and interaction. For others, its viability remains unquestioned and unqualified. The typically either/or character of this debate - that is, the tendency to regard mediating representation as necessary to any coherent account of knowledge and action *or* as a concept to discard outright - is nowhere more evident than when representation is considered in relation to the practices of scientists. The impasse between rational-cognitive and social-cultural accounts of how scientists produce knowledge [see, e.g., Longino (2002)] has much to do with radical positioning around 'representation'. The "black boxing" of cognition (and any appeal to representation) in some socio-cultural accounts (e.g., Latour & Woolgar, 1986; Latour, 1999) and the neglect of sociality and culture in traditional cognitive science models of the operation of formal symbol systems (e.g., Langley, Bradshaw, &Simon 1987) reflect radical, polar responses to the primacy of 'representation' as an explanatory concept.

Among the problems with this face-off is that neither social or cognitive accounts alone, nor accounts that position social and cognitive processes as parallel but interacting can adequately and richly account for the intricacies of practice evidenced by ethnographic observations of scientists at work or historical records of scientific practice. A purely socio-cultural or cognitive analysis, moreover, fails to offer the deep attention required to the material environments in which scientists practice: the objects, artifacts and instruments through which their problem formulation, framing, and innovations become possible.

Recent frameworks embracing a view of cognition as *distributed* across persons and artifacts and *situated* in physical and cultural contexts offer what seems necessary to bridge the artificial divide, namely a re-conceptualizing of both cognition and culture such that each is implicated in the other (Nersessian, 2005). Some of these efforts (e.g. Hutchins, 1995, Greeno, 1998, Clark, 1997, 2003) maintain a cognitive science identity and, in some instances, foundational cognitive concepts such as 'representation' remain, though unanalyzed in the new context. Increasingly, however, these efforts represent a conceptual and methodological distancing from "GOFAI" (Good Old Fashioned Artificial Intelligence), the classical or 'canonical' perspective on problem solving (Hutchins, 1995, p. 266) originally outlined by Newell and Simon (1972) in which cognition is contained within a "physical symbol system" which is typically interpreted as the individual learner or cognitive agent. The cognitive science language used in articulating the assumptions of these emerging frameworks does not alter the essential similarity of their mission and claims to those of earlier philosophical efforts to conceptualize consciousness and knowing as broader than the boundaries of the individual cognizing agent. As such, there are clear conceptual links to all previous philosophical efforts to construe the boundary between cognitive and social processes as porous at the very least (e.g. Gergen, 1994, 2000; Harre & Gillett, 1994; Mead, 1934; Vygotsky, 1978; Wittgenstein, 1953) . Indeed, some such links have been made explicitly (see, for example, Clark, 1997, 2003; Greeno, 1998). An important puzzle here, however, is how representation is maintained coherently as an explanatory concept in cognitive science frameworks that seek to situate their assumptions in philosophical traditions that notoriously eschew internal representation as traditionally formulated.

One prominent contemporary theoretical trajectory that maintains the notion of 'representation' argues for enlargement of the unit of analysis such that the boundaries of the cognitive system are conceptually expanded to the levels of local and broader cultural organization. Hutchins (1995a, 1995b) is pioneering in this regard; his notion of cognition as *distributed* draws from ethnographic analysis of "real world" problem solving processes. In *How a Cockpit Remembers its Speeds* Hutchins' unit of cognitive analysis is the cockpit of a commercial airline (1995a); in *Cognition in the Wild* it is "ship navigation as it is performed by a team on the bridge of a ship" (1995b, p. 49). In the first instance, the task of remembering the speeds on a typical descent from 30,000 feet followed by a successful landing is situated within the entire 'cockpit system' of captain, crew members and instruments in a particular physical and cultural space. What is purported to be genuinely new here is not the organizational level analysis in itself, of course, but "examination of the role of the material media in which representations are embodied, and in the physical processes that propagate representations across media" (Huthcins, 1995a, p. 266). Hutchins retains the computational metaphor, but describes computations as taking place via the "...propagation of representational states across media within the given cognitive system" (Hutchins, 1995, p. 373). The cognitive system of representation, manipulation, and dissemination of information, that is, includes both the embodied human agents, their patterns of communication and traditions of practice, as well as the material artifacts, devices, and instruments they use, the characteristics and functions of which in multiple ways support the dissemination of knowledge across the system. Internal media (memory, experience) intertwine (it is stronger than interact) with external media (data, diagrams, flow charts, graphs, instrument panels, etc). A related movement is *situativity* theory, which understands cognitive activities as interactions among agents and among agents and physical systems (e.g. Greeno, 1998). Nersessian calls these various positions "environmental perspectives" since "they make human action the focus for understanding cognition and take as their starting point that human cognition must be understood in relation to complex social, cultural, and material environments" (2005b, p. 3).

Although environmental perspectives acknowledge representations to be acquired and processed by cognitive systems with much wider boundaries than those of the "skin bag" (Clark, 2003), insufficient or inadequate attention has been given to the conception of representation required for compatibility with the assumption of cognition as distributed across this sort of system. Hutchins, for example, notes that representational media "may be inside as well as outside the individuals involved" (Hutchins, 1995a, p. 373), but purposefully makes no claim concerning the nature of the representations themselves, or how representation "inside" is to be understood, other than to list examples of internal media. While acknowledging that the media differ, his implication seems to be that the representations are of the same kind throughout the system. Although this is in the spirit of the original characterization of a distributed representation as forwarded by connectionist accounts, that is, of meaning emerging through the cooperative interaction of points in a representational space, deep conceptual complications are introduced with the mixing of categories (or media) in this space (e.g. persons and instruments). What seems required, at a minimum, is acknowledgment that as there are components of the system that are different in kind, there are different representational formats (equations, diagrams, physical models, forms of memory, for example), even if, as we believe to be the case, any one such format is incomplete or insufficient on its own. Important questions then concern how and to what extent these formats mesh synergistically. In short, representation in the systems conceptualized by distributed and situated perspectives must have different roles and be different in nature from representation in GOFAI or connectionist accounts, and the problem deserves more clarification than it has tended to receive.

'Distributed representation', moreover, is surely quite different from the conception of representation that has been the most frequent target of criticism among practice theorists, namely the structure located only "in the head" that mediates between world and experience (e.g. Lave, 1988; Still & Costall, 1987). Simply making the target *mental* representation is not sufficient if one broadens the concepts of 'mind' and 'mental' such that they"leak" into the environment, as implied by Clark (1997, 2003), Hutchins (1995) and others. Nor, then, can we maintain a clean division between *internal* and *external* representations ('external' being conceived as graphs, pictures and diagrams, for example, as used in science practice), or representations "inside" *or* "outside" a person, as Hutchins puts it, or simply replace "representational" with "inscriptional" (e.g. Pea, 1997). The notion of purely external representation is as problematic as the notion of purely mental representation, as Goodman (1988) argues. The internal/external dichotomy works only if we locate processing within distinct boundaries, such as a mind/brain inside a head. If the processing system (whatever we call it) is conceptualized as an entire problem space (such as a cockpit, its communicative practices, traditions and *telos)*, it becomes very difficult to identify representations external to that system, just as it is difficult to draw firm lines around the system itself. Indeed, references to representations "inside or outside a person" seem to contradict the framework and foundational assumptions of distributed approaches.

Thus the purpose of this paper is to explore possibilities for conceptualizing representation in a way more compatible with and useful to recent distributed and situated accounts of cognition, particularly as informs the practice of science. We emphasize "explore," in that we primarily provide illustrations from a set of interviews with engineers and scientists that highlight the problems of interest and help us show how the target concepts might be conceptualized in novel ways. The account we aim at as our research develops is one that eschews rigid internal/external distinctions and construes representations, specifically model-based, organized representations, as created and used in the cooperative practices of persons as they engage with natural objects, manufactured devices, and traditions, as they seek to understand and solve new problems. Both Reed (1987) and Heft (2001) made headway in conceptualizing systems of representation as compatible with frameworks arising from ecological psychology, as we will discuss at the end. Yet there is more to be done, particularly when the focus is turned specifically to the practices of research scientists, engaged in the increasingly complex and flexible problem solving necessary to innovation.

Our problem space: Exploring cognition and learning in interdisciplinary laboratory cultures

Our efforts toward this end are informed empirically by a wide-scale, multi-year study. The analytic framework for the study builds upon previous work of Nersessian's, including the results of prior research centered on interpreting model-based reasoning practices of scientists and situated reasoning practices in science education (e.g. Nersessian 1992, 1995, 2002). We approach data collection and interpretation with the assumption that cognition, both in mundane and scientific practices, comprises a complex system of persons, devices, artifacts, instruments, texts, and traditions.

We are studying two biomedical engineering research laboratories situated on a university campus, and are seeking to describe and understand the learning, reasoning and problem solving practices of both the novice and expert researchers who work in them. These are interdisciplinary and innovation-seeking communities, which strive to develop new ideas and applications at the cutting edge of their fields. In previous work, our research team has emphasized that each "lab" might be understood not simply as a physical space containing the instruments and devices of the area of practice but also as an organized social group of science practitioners with a broad, shared agenda (Nersessian et al., 2003). This shared agenda is informed by the assumptions and goals of each lab's principal investigator but is dynamically influenced by the problem formulation, problem solving, and insights of all members of the laboratory community. The epistemic culture (Knorr Cetina, 1999) of the laboratory is altered continuously by the entry of new researchers and the departure of others, changing not only the social composition but the knowledge resources and the projects and problems with which the lab is concerned - Researchers, problems, and technologies all develop and change. Thus we construe each laboratory as an evolving problem space and an evolving learning culture, embedded within a history and in a set of conceptual and practice relationships to the wider field and its traditions. Of interest, too, is that biomedical engineering (BME) is inherently interdisciplinary, drawing its resources from both biology and engineering, as it applies engineering methods to biomedical problems. The interdisciplinary nature of the research culture helps to distribute expertise and creates a need to seek out help and apprenticeship as appropriate to the task at hand. All lab researchers, including undergraduate students, are encouraged to make important research contributions; none are relegated to "technician" status.

Lab A, a tissue engineering laboratory dating to 1987, examines living cells and tissues and applies engineering practices to develop artificial blood vessels. Engineered substitutes for biological tissues, locally called "constructs," must replicate the function of these tissues. Environments necessary to test the functioning of engineered tissues are designed; these replicate the relevant aspects of the environment of the human body such as an artery. Lab members have various engineering backgrounds. Lab D is a neuroengineering laboratory dating to 2002 that investigates learning in a "dish" of cultured neurons. The dish embodies the neuron culture by connecting it to artifacts capable of motion within an environment - real-world or computationally simulated. Lab D researchers have backgrounds in biochemistry, neuroscience, and mechanical engineering. Members of both labs are, thus, working in hybrid biology/technology environments.

To investigate the cognitive and learning practices in these labs we use a mixed methodology of ethnographic research and cognitive-historical analysis (Nersessian, Kurz-Milke, & Davies, 2002). Although both cognitive-historical analysis, which uses historical records to unpack the reasoning and methodological practices of scientists (e.g. Nersessian, 1984, 1992; Tweeny, 1985), and ethnographic studies of the situated meaning-making practices of scientists (Latour & Woolgar, 1986; Bucciarelli, 1994, Knor Cetina, 1999) have contributed substantively to science studies, the two methodologies have not been combined as they are in this project. This combination of methods facilitates the integration of cognitive and cultural accounts by enabling a description along recognizable cognitive categories of the creation, use, and evolution of research practices as they are situated in the cultures of knowledge production.

Our own research group is interdisciplinary, with backgrounds in computer science, anthropology, linguistics, cognitive psychology, theoretical psychology, and history and philosophy of science. We work on different aspects of data collection and analysis and share our progress and thinking in regular group meetings to which everyone is encouraged to contribute. All participants receive training in ethnography and/or cognitive historical analysis, and there is a genuine sharing of conceptual and methodological expertise from our various background disciplines. Undergraduates, MS and PhD students have made significant contributions to the analysis and conceptual framing. Our group has invested over six-hundred hours in observing researchers actively working in the laboratories (on the "benchtop") and talking to them about their work. We have had guided tours of the laboratory, have obtained audio-visual recordings of journal club and other group meetings, and have examined notebooks and other aids kept by researchers, including formal and informal diagrams used for formulation and communication of ideas. The bulk of the data we have thus far coded, and that which is principally employed in the analysis for this paper, is a set of interviews with members of both labs, from undergraduates new to biomedical engineering to graduate students at various stages to the supervising principal investigator. To date we have collected approximately 150 audio and video recordings. Our assumption is that representational and reasoning practices can be discerned in part from the way researchers describe what they are learning and how they are thinking about problems. With some lab members we have conducted interviews at two week intervals over several years, thus we are able to interpret developments in thinking chronologically, through case study analysis. The interviews are of different types and have different foci. Some are aimed at obtaining the lab member's account of her experience, adjustment, and progress in the lab, some have the aim of collecting accounts of the development and use of technology used in problem formulation and solving, and some are interviews focused more explicitly on mentoring relationships or gender relations in the laboratory cultures.

Interpretation of these data, particularly the interviews, is broadly guided by the principles and techniques of grounded theory (Glaser & Strauss, 1999), using a process of constant comparison and analytic induction to develop conceptual categories and coding schemes toward a theoretical account of cognitive practices and learning in the labs. Most of the interviews remain to be analyzed, thus this account represents work in progress, though the second author has devoted a substantial portion of her career to the analysis of the use of model-based representations in science practice, and this informs our analysis.

Here we present two interrelated interpretive notions emerging from our analysis that have particular relevance to the project of providing an account of representation compatible with the assumption that cognition is distributed. Consistent with our methodology, the concepts developed here are held tentatively as we continue our data collection and analysis. The goal here is to illustrate how these concepts might be understood in the context of the research labs.

Core Interpretive Notions: 'Cognitive Partnering' and 'Representational Coupling'

Cognitive Partnering

We understand 'cognitive partnering' as an expression of cooperative participation within an epistemic culture that enables or sustains particular cognitive-cultural practices. Cognitive partnering is of two overlapping varieties: partnering among persons, for which we have distinguished two sub-categories: peer-to-peer partnering and mentor-to-apprentice partnering (though mentoring relationships can also be informal and reciprocal), and person-to-artifact partnering.

a. Person to person cognitive partnering

An interview passage from lab A illustrates how we understand person to person cognitive partnering. 'Construct' here is a local term for an artificial blood vessel, a 3-D environment manufactured to embed cells and thus simulate the bodily environment of a blood vessel. Specifically, constructs are tubular shaped grafts that function as models of blood vessel walls in experimental situations.

I: What's your notion or sense of where your research is headed?

A22 *I'm going to be working with—I still need to learn more about it but I'll be working with the fabrication of constructs with the possibility of either looking at different methods of fabricating constructs, or making basically a construct within a construct.*

I: So what—I've never heard that before—"construct within a construct?"

A22. *Yeah, this was an idea that A13 had. I guess A11 has actually done something similar, but looking at doing a construct with an inner layer that the collagen with smooth muscle cell and then an external layer which is a collagen, which is simply collagen without muscle—without cells-and then, and using that. I guess A11 actually did something that was very similar but in reverse order, with the smooth muscle cells on the outside.*

The second agenda option A22 gives here, that of making "the construct within a construct" is most interesting because she frames it as an idea originated by another lab member, A13 (though note that it she is unclear whether the idea or method originated with A13 or A11). In either case, both the notion of a ‘construct within a construct’ and the practice of building such a device are specific to the culture of Lab A. As such they are identified initially with a specific member of Lab A and credited to him (A13). The making of a “construct within a construct” is distinguished in this sense from activities such as cell culturing which would be common to all tissue engineering labs. But of interest is A22 seems to have appropriated the notion and the practice from another lab member that affords ways for her to frame her research agenda (in answering the question concerning where her research is heading). Moreover, the construct itself is a representation - a physical model - as we will discuss when presenting the concept of representational coupling.

The cooperation facilitating cognitive partnering need not be purposeful or explicit, though in other cases it is more so. Here, for example, A22 describes several forms or styles of collaboration facilitating her learning of cell culturing techniques

A22: *I learned some from A5, and I’ve worked with A7, and I’m probably going to work a little bit with A10 this morning too*.

I. And how do they—how do they teach you to do that?

Well, A5 - we sat down and she worked with me. She showed me: we got cells, we had six different groups, she showed me like three of the cell cultures, and then she watched me and corrected me as I did the other three. And then I just came back and kept doing it and if I had any questions I could ask. And with A7, mostly I’ve just been watching her work, so far. And then today, this morning I’m going to be doing trypsynizing where basically A10’s going to tell me what I need to do and I’m just going to watch. I mean he’s going *to watch me and make sure that I do it correctly*.

Thus, A22 is experiencing several partnerings that enable her to acquire the cognitive practices surrounding the use of the central artifacts of the research in this lab.

b. <u>Person to artifact cognitive partnering</u>

Cognitive partnering with artifacts is an expression of working cooperatively with specific artifacts to carry out particular research goals. An explicit example comes from Lab D:

D4: *Well, that way I'm strengthening that particular pathway, so the network would prefer to always excite these two cells in a certain way after my modifying input. Maybe they weren't before my modifying input, and after my modifying input the pathway becomes stronger.*

Our understanding of cognitive partnering between person and artifact has been informed in part by what we have observed as frequent practice in the researchers' description of their work, namely the attribution of something like *agency* to objects, artifacts, and devices, most clear in the practice of anthropomorphizing:

D6: *Cells make a lot of decisions with whom they want to connect with.*

D6: *So this computer is listening, and what it's listening to you can think of as the motor output*.

D4: *Today the dish* [dish of neurons] *is happy*

A11: *The cells once they are in the constructs will reorganize it and secrete a new matrix and kind of remodel the matrix into what they think is most appropriate.*

We construe such expressions as indicating a sympathetic engagement with artifacts and devices and a tacit sense of working together with them toward problem solving goals. This practice becomes more pronounced as members progress as researchers - as they develop a sense of research as a cooperative enterprise not only with others but with the devices essential to carrying out their research. In cognitive partnering the researcher needs to be able to take the perspective of the artifact as illustrated by the respondent's invoking a cell's perspective in articulating why the chamber of the flow loop device in which the construct is subjected to the kinds of shear stresses experienced *in vivo* is not itself an approximation.

I. How about the—how about the size of the chamber. Is that—is that part of the- is that an approximation, or...

A10: *Well, no in the sense that it doesn't really approximate. Most arteries we look at are going to be smaller than that surface. But from a cell's perspective, the cell sees basically a flat surface. You know, the curvature, is maybe one over a centimeter, where as the cell is like a micrometer. You know, like 10 micrometers in diameter. It's like ten thousandth the size. So to the cell - it has no idea that there's actually a curve to it.*

That is, A10 casts the cells as experiencing a "flat land" environment in the artery and infers that the fact that the constructs are cut open and laid flat in the flow loop chamber does not constitute an approximation, but actually replicates that experience.

The notion of cooperative engagement and perspective taking with laboratory artifacts, most often the simulation devices, complements the language of partnering which we find important to our describing the distribution of representation in the laboratory cultures.

II. *Internal-External Representational Coupling*

Solving problems in the cognitive-cultural problem space of a biomedical engineering laboratory, we claim, requires specific kinds of partnering of persons and of persons and artifacts to achieve cognitive goals. To highlight specifically the representational practices enabled by this partnering, we have developed a concept we call internal - external representational coupling. We use ‘internal’ and ‘external’ loosely here, since, as noted, we consider the traditional internal/external divide to be artificial. The notion of ‘coupling’ is the important element; it is a counterpart to the notion of partnering. One *has* a partner, but one is only a *part* of a couple. In this discussion of representation we focus on what we consider to be the most interesting and fruitful aspect of representational practice, namely the capacity for reasoning through models, physical and mental.

A growing body of work in science studies establishes that much of scientific inquiry involves creating and using models of all kinds in experimental and theoretical work. Contrary to the standard view of scientific reasoning as hypothetico-deductive or logic-based in nature, for example, modeling and “model-based reasoning” practices are the *signature* of much research in the sciences, both in discovery and application (Cartwright 1983; Giere 1988; Hesse 1963; Magnani, Nersessian, and Thagard 1999; Morgan and Morrison 1999; Nersessian 1984, 1992, 1999, 2002, 2002)). Studies of historical science provide evidence that although scientists have developed new tools for enhancing and expanding these practices, since the inception of science creating and using models has been a standard part of practice. A model can loosely be characterized as a representation of a system with interactive parts with representations of those interactions. Models can be qualitative , quantitative, and/or simulative (mental, physical, computational).

Models, then, are organized representations, the representation of things in relation to one another. Model-based reasoning, as Nersessian has stressed, is a practice of problem solving through constructing models, physical and mental, that represent the salient dimensions of the target phenomena, and drawing inferences from manipulation of the model. Further, she has argued that the cognitive basis for the scientific practice lies in the mundane cognitive capacity to construct and reason with mental models.

The literature on mental modeling is vast and much remains to be clarified, yet the general notion remains useful for understanding scientific reasoning and other practices, particularly when the focus is on the construction and use of models during reasoning and their role in relation to working memory, implicit and explicit. As such we make no claim as to the ontological status of models other than to construe them, like memory itself, as part of the cognitive-cultural system in which people act. Nor do we consider here the place and nature of models in long term memory, though of course reasoning must engage long term memory. The emphasis for us is on reasoning *through* models, understood as a cognitive-cultural practice, one of dynamically using visual, analogical, and simulative reasoning together toward the creation of working models - mental and physical - that define the problem space and allow creative manipulations (Nersessian, 1999). Following Craik's (1943) early formulation of models and the mental-modeling framework as this has developed in cognitive science (e.g., Johnson-Laird, 1983), we understand a model to be a structural, functional, or behavioral analog of a situation, event, process, or entity.

Nersessian's cognitive-historical studies in physics support the claim that a signature practice of science is constructing models or interlocking model systems that abstract and organize information provided in different representational formats, including equations, diagrams, and linguistic representations. Our ethnographic investigation of biomedical engineering labs suggests, too, that the cognitive practices of even beginning researchers in the laboratory community can be similarly understood in terms of the construction and use of interlocking models, and that this practice facilitates understanding and technological innovation. Moreover the ethnographic investigation affords a view of how the artifacts and engineered devices of the laboratory function as part of model systems within the distributed cognitive processes. Here is an example from an interview that illustrates the kind of practice we are seeking to understand, and for which we think the notion of reasoning through constructing and manipulating models is beneficial. The interview begins with a questions about an device commonly used in Lab A, the pulsatile bioreactor that has been created to manipulate the constructs:

I. Why don't you just tell me briefly what the bioreactor is?

A16: *So the bioreactor is used for stimulating the constructs, so we make the constructs, and we want to stimulate them, in a way that's similar to a way that they'd experience in vivo. So, the bioreactor gives pulsatile distension to the constructs, and is supposed to sort of simulate what they are supposed to feel in the arterial flow.*

I. And how does it work? How does it do that?

A16: *So we have a pump, that provides pressure and there's a sort of mech- ....an electronic switch that flips back and forth, and allows the pressure to either be on or the pressure to be off. And that cycles a one hertz. So basically we have liquid in a reservoir, and that's used as an incompressible fluid similar to the blood. And essentially the pressure, -- is forced down upon the liquid, the media that's in that reservoir.*

This passage illustrates the *in vivo*/ *in vitro*/*ex vivo* distinction through which Lab A practices may be understood as inherently representational. Artificial blood vessels are representations of 'real' blood vessels, and they must be tested in an environment other than the human body in which they will be implanted. Thus researchers must design *in vitro* simulations of the *in vivo* environment and *ex vivo* (animal model) implantation environments to serve as sights for experimentation. The bioreactor is one *in vitro* environment - a model of blood behavior that manipulates another model of a blood vessel, the construct. A passage from another Lab A researcher also makes the representational nature of the engineered models clear:

> A5: "*We use the flow loop as um, a first-order approximation of a blood vessel environment, in that as the blood flows over the lumen, the endothelial cells experience a shear stress*."

Thus the construct and flow loop, engineered devices, are representations of physical environments that instantiate part of the working model of the phenomena and allow for simulation and manipulation, serving as sites for experimentation and enabling inferences. One researcher aptly referred to the process of constructing and manipulating these *in vitro* physical models as *"putting a thought into the bench top and seeing whether it works or not*."

These instantiated "thoughts" that afford controlled simulations of *in vivo* contexts, such as local forces at work in an artery, are of focal points of our project of understanding representation in the distributed systems of Lab A. In this practice researchers construct and manipulate 'internal' models of both the phenomenon and the device and an 'external' model that is the device, each being incomplete on its own in the problem-solving process. In A16's description of the representational device and its relation to another device, the construct, there is evidence of an organized understanding of component parts that we describe as a model of device composition: the pump, the switch, the liquid in the reservoir, their functions, and how these interrelate to perform the task of stimulating constructs. The understanding is of a representation of a phenomenon that satisfies constraints drawn from the problem domain, for example, spatial, temporal, causal, logical, categorical, or mathematical constraints, as well as constraints of the physical device itself, such as the engineering constraint of the flow loop as a "first-order approximation."

An example of an inference afforded by manipulating a model of an engineered device is evident in the following:

> A22: *...this [a construct within a construct] was an idea that A13 had. I guess A11 has actually done something similar, but looking at doing a construct with an inner layer that the collagen with smooth muscle cell and then an external layer which is a collagen, which is simply collagen without muscle—without cells-and then, and using that. I guess A11 actually did something that was very similar but in reverse order, with the smooth muscle cells on the outside*.

The reference here to reverse order suggests not only a structural model of the construct within a construct but a temporal or sequential order of the process by which it was constructed, and suggests a manipulation of this model through the imagining of the order being reversed by A11. Reasoning through the construction and manipulation of a model can be aided by visualization and analogy, as in the following example. When asked about the practice of cutting the construct open and 'flowing' it flat rather than in tubular form as *in vivo* the researcher responded:

A10*: Maybe we could think of it as, for instance, if you think of your scale, right? If you look at a blood vessel, from this scale, it looks like a tube. If you were a millimeter tall, then they* *look pretty flat. So we use that as our approximation of the tubular surface.*

Traditionally, memory, inference, and visualization would be ascribed as the mental contribution. In considering the internal and external representations and processes involved in simulative model-based reasoning as a coupled system, we contend that the ascription of 'mental' to a model might better be construed as pertaining more to the property that inferences are generated from it than to a locus or medium of operation.

Combining the concepts of cognitive partnering and representational coupling, another example from Lab A illustrates how the contributions of both researcher and artifacts, that is, their cooperative partnering, enables representational practices of various kinds.

> I.: You learned how to make blood vessel constructs? ... So how do you do that?
>
> *A22: First you have—you have to figure out what cells you want to use, you use trypsin and you take them off the plate and then suspend them and then put them in media, in new media, and you suspend them and count them—how many cells you have and based on that, based on how many cells you have, how many constructs you have it - there's a spread sheet that someone's come up with that you determine how much solution you need, because if you're assuming that you did a good job and it's equally spread throughout, and then I have a nice little cheat sheet to go by which is much more helpful, then you have little tubes that you—I may get it wrong, I'm going by memory and I always have a little cheat sheet there in front of me.*

This passage depicts an organized understanding of cells in relation to trypsin, the plate, and the activities of suspending and counting cells. Moreover it gives the impression of being a shared understanding or model of the procedure for making constructs, as noted, one that A22 has learned from other lab members. There is also reference here to the shared representational practice of using a spread sheet to determine the amount of solution needed, admittedly less helpful than the personal cheat sheet A22 uses as a heuristic. This passage is also interesting because it calls attention to the material or cultural artifacts necessary to the cognitive practice of counting the cells, a form of representing them needed to determine the amount of solution required. We have underlined the factors contributing to this task, the contribution of the agent: figuring out what cells she wants to use, the trypsin, the suspension in new media, the cells, the constructs, the spread sheet, and the little tubes. Interesting here, too, is that this is the first time in the set of interviews that she has used the term trypsin (itself a technical artifact) confidently, without hesitation or qualification.

References to what would be traditionally called ‘external representations’ are also common in the interviews. What is most interesting to consider is how the practice of using drawings and other representational techniques supports not only thinking and problem solving, but what we have called ‘cognitive partnering’ itself. Here A31 discusses the goal of developing a process that will generate a high yield of endothelial cells, which he describes as the ‘really big picture’ of his agenda

A31 *But that’s the really big picture*.

I. The big picture?

A31 *So do I need to get you a cd with the drawings on it? Do you want the drawings, or can I give you like the three dimensional rendering of it?*

I. That’d be great, that’d be great. I think it would be interesting to see the different sketches; so you’ve sent those off already?

A31 *We're sending off the base, the back, and the struts today. ...It's amazing how much time you can spend. I made the drawings probably two weeks ago, and I've been revising 'em and making them. You know, I never really thought about it, but you need to make it as easy as possible for the machinist to read.*

Later in the interview, A 31 discussed his desire to design a bioreactor and the mentoring steps (person-to-person coupling) taken to enable him to develop the competence to do so:

I. So how did you. . . I mean, did she just say, 'ok, go out and design the bioreactor, and just let you loose, or....?

A31 *we, she . . . we meet a lot...I'll do something, you know, she would..., what we did is... she taught me how she designed stuff, I think at XXX. We started out with, she called it the QED table where you write out what it needs to do, what it, what you want it to do and what it would be nice if it did. So we filled this out and we met and we talked about it and I went back and changed some things and then showed it to her again at a meeting a couple of days later. She was like, this is...looks good. You know, so I came up with some preliminary sketches based on that, like, ok, if it needs to do this then how can I make it do this and I started out with, you know, I started out with wa-a-ay too complicated a design . . . and it would've been really expensive to make cause I had no idea to even think about that stuff, so she'd be like, you know, you don't need to do this; you don't need this, and I'd go back and re-draw everything on paper, you know, and after a couple, two or three meetings like that, it was like, ok, this is you know, we're getting close; why don't you start putting the parts together in solid works, and I'd start doing it, uh parts, and then making them into assemblies, making sure things fit, and* *show it to her, and after a while it was pretty simple.*

Collectively, these interview segments - as well as many more we could provide - demonstrate how cognitive partnering and representational coupling come together in the course of learning and conducting research, which are inseparable facets of the kind of cognitive-cultural systems we are studying.

Conclusion

Given that the internal - external divide permeates the language of our culture, it is difficult to find language that adequately conveys the co-constitutive nature of culture and cognition that we believe to be mandated empirically and philosophically. We have used the language of partnership and coupling, guided consciously by previous work (e.g. Beer, 1995; Prinz & Barsalou, (2000); Hegerty, 2004) and perhaps unconsciously by cultural conceptions of marital partnering as the 'joining of two persons into one flesh'. However far from the realities of marriage, the 'two as one' notion does come close to expressing the kind of relationship of cognitive and cultural domains that enables these to be understood as a single system, each being intimately implicated in the other.

Moreover, the intimate language used to express relations in laboratory cultures seems fitting in view of the affective, motivational, and identity aspects of representational practice that we have no space to develop here. Affective experience of researchers in relation to one another and to their work, including transformations in their feelings of belonging and investment in the work of the laboratory, cannot be eliminated from the cognitive-cultural system that creates and sustains representational and learning practices. Thus, for example, we are looking at affective language about laboratory experience (including such seemingly throwaway phrases such as “that was cool”!) and changes in level of esprit de corps, as evidenced, for example, by shifts in pronoun use from *I* and *they* to *we*. We are also interpreting expressions of a nurturing or care-taking identity in relation to cells and other artifacts, as these co-occur with the framing and representational practices of BME researchers.

Before concluding this brief introduction to a complex problem we address an issue basic to our enterprise: the need for representational language in the first place. If, as noted initially, representation is foundational to traditional cognitive science and cognitive psychology, should not ‘post-cognitivist’ thinking strive to avoid reference to representation at any cost? Clearly, ‘pre-cognitivist’ forerunners of post-cognitivist thought, e.g. Dewey, Mead, and Heiddeger, found it necessary to avoid any appeal to representation to sensibly conceive of a socialized mind. It is important to recognize, however, that it is a particular conception of representation, a remnant of enlightenment formulations of 'idea', with which critics of representational theories of mind are working. This is not a necessary conception. Representation, though traditionally tied to a dualistic ontology, when framed as practice may, as any practice, be construed as distributed or “stretched over, not divided among” (Lave, 1988, p.1) thought, body, action, tradition, persons, artifacts, devices, and physical space. The traditional targets of criticism related to representation, namely its function to isolate cognition from the material world, and the dubious ontology of, for example, a language of thought, are not relevant to a notion of representation as distributed in these ways.

This is not to say that all the kinks are ironed out. As noted, this line of research, including our analysis, is very much in progress. We have focused on the distributed nature of representation here, but we must also carefully consider how representation is both distributed and embodied, and how it is both distributed and individual. One way forward is through a neurological approach, such as that of Barsalou (1999), to addressing questions concerning the nature of the symbol structures that constitute representations. On Barsalou's account, cognitive processing employs "perceptual symbols," which are neural correlates of sensorimotor experiences (Barsalou, 1999). These symbols "result from an extraction process that selects some subset of a perceptual state and stores it as a symbol" (Barsalou & Prinz, 1997, p. 275). The relationship between the symbols and what they represent is analogical, i.e., that of similarity, as opposed to arbitrary, as with a language string. This developing theory is supported by mounting evidence that perceptual and motor processes play a significant role in many kinds of cognitive processing traditionally conceived as separate from these, including memory, conceptual processing, and language comprehension [See, e.g., (Barsalou, 1999, 2003; Barsalou, Simmons, Barbey, & Wilson, 2003; Barsalou, Solomon, & Wu, 1999; Catrambone, Craig, & Nersessian, 2005; Craig, Nersessian, & Catrambone, 2002; Glenberg, 1997b; Johnson, 1987; Kosslyn, 1994; Lakoff, 1987; Solomon & Barsalou, 2004; Yeh & Barsalou, 1996), and evidence from neuropsychology that the perceptual system plays a significant role in imaginative thinking (See, e.g., (Farah, 1988; Kosslyn, 1994)]. Despite the many questions relating to how perceptual representations account for abstract concepts, they might better serve the requirements for representational coupling, i.e, interfacing between external and internal representations.

Another means of proceeding is to revisit the insights of earlier pragmatist and ecological perspectives in light of contemporary concerns with embodied and distributed representation. Mead (1932, 1934), for example, extended sociality to material things, and developed a notion of perspective-taking that can be applied to our concept of cognitive partnering between person and artifact, in particular the anthropomorphizing we are observing in our interviews. Few have given the problem of understanding the individual within the collective more careful deliberation than Mead, or made more rigorous effort to relate the relationship of individual and collective to the world of natural objects. Of particular interest to this discussion is Mead's notion that human and non-human agents together comprise the situation within which one acts, with inanimate objects construed as part of the sociality from which the individual mind and self emerge. In a footnote to the discussion on his concept of the "generalized other" from which self he acknowledges that "it is possible for inanimate objects, no less than for other human organisms, to form parts of the generalized and organized—the completely socialized—other for any given human individual. . . Any thing, any object or set of objects, whether animate or inanimate, human or animal, or merely physical—toward which he acts, or to which he responds, socially, is an element in what for him is the generalized other" (1934, p. 154; of recent interest see also Martin, 2005).

Moreover, Gibson (1979), despite some analyses to the contrary, never argued that indirect or mediated awareness was impossible, though he came to what Reed has called "an entirely new definition of indirect perception" (Reed, p. 149). "Images, pictures, and written-on surfaces," notes Gibson, "afford a special kind of knowledge that I call mediated or indirect, knowledge at second hand" (1979, p. 42). He specifically mentioned devices and instruments, and drawings, paintings and verbal descriptions and measurements, as that which facilitates or "consolidates" knowledge *about* the environment (which Gibson distinguished from knowledge *of* it, obtained directly); as such they might be understood as what we would call cognitive partners. Reed, in later work, has begun to develop an account of representational systems through which knowledge of the shared environment gained through direct perception can be "selected, highlighted, made explicit, and shared" (1987, p. 152). These involve cultural and historical as well as individual psychological processes on his account. "In humans, the cultural and the individual ('natural') processes are thoroughly mixed," (p. 162); quoting Gibson he added, "mediated apprehension gets combined and fused with direct apprehension" (Gibson, 1976? 5-75), Reed p. 162). This kind of fusion is vitally important to understanding the cognitive-cultural system, and specifically the concept of distributed representation.

So construed, of course, representation is a vehicle of communication with bidirectional effects within a distributed space, rather than a mechanism that severs the individual from the social and material worlds. Representation creates culture and transmits it, including the cultures, both broad and narrow, that constitute science. Models, like representations more broadly, cannot be meaningfully understood as internal or external phenomena in isolation; the appropriate unit of analysis is practice broadly construed, and this practice expands across traditional internal and external realms. It is irreducibly *both* internal and external, though for sake of analysis we seek descriptions at different levels, or of different constituent components. We would add to this that representation, in particular the notion of model-based representation, affords a way of thinking about innovation and creative reasoning in scientific practice. In scientific reasoning, models are engaged or invoked in multiple formats: diagrams, drawings, equations, language, and gesture. This engagement with models affords manipulation of constructed simulations, leading to new ways of thinking about phenomena and new problem solving applications. A student member of our research team recently referred to models as being 'enacted' in various ways in the laboratory. "Enactment" is an apt description because it captures the dynamism of cognitive partnering and representational coupling in these evolving cognitive-cultural systems. We offer the 'enactment of models', especially through cognitive partnering and representational coupling, as a promising way of understanding representation as distributed.

Acknowledgements

This research was made possible by the support of the National Science Foundation ROLE Grants REC0106773 and REC0450578 to Nancy Nersessian and Wendy Newstetter. Nersessian also acknowledges the support of grants from the Radcliffe Institute for Advanced Study and the National Endowment for the Humanities. The views expressed are not those of the granting agencies. We thank our research subjects for allowing us into their work environment and granting us numerous interviews. We acknowledge the myriad contributions to this project of the present and past members of our "Cognition and Learning in Interdisciplinary Cultures" research group, especially Wendy Newstetter. Special thanks go also to Elke Kurtz-Milke for her conceptual and methodological contributions to the broader project.

References

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences,* 22(4), 577-609.

Barsalou, L. W. (2003). Situated simulation in the Human Conceptual System. *Language and Cognitive Processes,* 18(5-6), 513-562.

Barsalou, L.W., Simmons, W. K., Barbey, A. K., & Wilson, C. D. (2003).Grounding conceptual knowledge in a modality-specific system. *Trends in Cognitive Science,* 7(2), 84-91.

Barsalou, L. W., Solomon, K. O., & Wu, L. L. (1999). Perceptual simulation in conceptual tasks. In Hiraga, M. K., Sinha, C., & Wilcox, S. (Eds.), *Cultural, typological, and psychological perspectives in cognitive linguistics: The proceedings of the 4th annual conference of the International Cognitive Linguistics Association* (Vol. 3, pp. 209-228). Amsterdam: John Benjamins.

Beer, R.D. (1995). A dynamical systems perspective on agent-environment interaction. *Artificial Intelligence*, 72, 173-215.

Branquinho, J. (2001). Introduction. In *The foundations of cognitive science.* Oxford: Oxford University Press.

Cartwright, N. 1983. *How the Laws of Physics Lie*. Oxford: Clarendon Press.

Catrambone, R., Craig, D. L., & Nersessian, N. J. (2005). The role of perceptually represented structure in analogical problem solving [in press]. In *Memory and Cognition.*

Cole, M., & Engestrom, Y. (1997). A cultural-historical approach to distributed cognition. In In G. Salomon (Ed.), *Distributedcognitions: Psychological and educational considerations.* Cambridge: University Press

Craik, K. (1943). *The nature of explanation.* Cambridge: Cambridge University Press

Dewey, J. (1910). How we think. Lexington, MA: DC Heath

Farah, M. J. (1988). Is visual imagery really visual? Overlooked evidence from neuropsychology. *Psychological Review,* 307-317.

Fodor, J. (1981). *Representation: Philosophical essays on the foundations of cognitive science.* Cambridge: MIT Press.

Gergen, K. (1994). *Toward transformation in social knowledge*. Thousand Oaks, CA: Sage.

Gergen, K. (1999). *An invitation to social construction*. Thousand Oaks, CA: Sage

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Giere, R. N. 1988. *Explaining Science: A Cognitive Approach*. Chicago: University of Chicago Press.

Glaser, B. G. & Strauss A. L. (1999). *The discovery of grounded theory, Strategies for qualitative research.* New York: Aldine.

Glenberg, A. M. (1997). Mental models, space, and embodied cognition. In T. Ward, S.M.Smith, & J. Vaid (Eds.), *Creative thought: An investigation of conceptual structures and processes* (pp. 495-522). Washington, DC: American Psychological Association.

Greeno, J. G. (1998). The situativity of knowing, learning, and research. *American Psychologist,* 53(1), 5-24.

Harre, R., & Gillett, G. (1994). *The discursive mind.* London: Sage.

Heft, H. (2001). *Ecological psychology in context.* Hillsdale, NJ: Lawrence Erlbaum.

Hegarty, M. (2004). Mechanical reasoning by mental simulation. *Trends in Cognitive Sciences* 8(6), pp. 280-285.

Hesse, M. 1963. *Models and Analogies in Science*. London: Sheed and Ward.

Hutchins, E. (1995). *Cognition in the wild.* Cambridge MA: MIT Press.

Hutchins, E. (1995). How a cockpit remembers its speeds. *Cognitive Science*, 19, 265-288.

Johnson, M. (1987). *The Body in the mind: The bodily basis of meaning, imagination, and reason.* Chicago: University of Chicago Press.

Johnson-Laird, P. N. (1983) *Mental Models*. Cambridge, MA: Harvard University Press.

Knorr Cetina, K. D. (1999). *Epistemic cultures: How the sciences make knowledge*. Cambridge: Harvard University Press.

Kosslyn, S. M. (1994). *Image and brain.* Cambridge, MA: MIT Press.

Lakoff, G. (1987). *Women, fire, and dangerous things: What categories reveal about the mind.* Chicago: University of Chicago Press.

Langley, P., Bradshaw, G. L., & Simon, H. A. (1987). Heuristics for empirical discovery. In L. Bolc (Ed.), *Computational models of learning*. Berlin: Springer-Verlag.

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies.* Cambridge, MA: Harvard University Press.

Latour, B., Woolgar, S. (1986). *Laboratory life: The construction of scientific fact* (2nd ed.)

London: Sage.

Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life.* Cambridge: Cambridge University Press.

Martin, J. (2005). Perspectival Selves in Interaction with Others: Re-reading G.H. Mead's Social Psychology. *Journal for the Theory of Social Behaviour* 35 (3), 355-358.

Magnani, L., N. J. Nersessian, and P. Thagard, eds. 1999. *Model-Based Reasoning in Scientific Discovery*. New York: Kluwer Academic Publishers/Plenum.

Mead, G. H.(1932). *The philosophy of the present*. Chicago: Open Court Publishers.

Mead, G. H. (1934). *Mind, self, and society*. Chicago: University of Chicago Press.

Morgan, M. S., and M. Morrison, eds. (1999). *Models as Mediators*. Cambridge: Cambridge University Press.

Nersessian, N. J. (1984). *Faraday to Einstein: Constructing Meaning in Scientific Theories*. Dordrecht: Martinus Nijhoff/Kluwer Academic Publishers.

Nersessian, N. J. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In *Minnesota Studies in the Philosophy of Science*, edited by R. Giere. Minneapolis: University of Minnesota Press.

Nersessian, N. J. (1992). In the theoretician's laboratory: Thought experimenting as mental modeling. In *PSA 1992*, edited by D. Hull, M. Forbes and K. Okruhlik. East Lansing, MI: PSA.

Nersessian, N. J. (1999). Model-based Reasoning in Conceptual Change. In *Model-Based Reasoning in Scientific Discovery*, edited by L. Magnani, N. J. Nersessian and P. Thagard. New York: Kluwer Academic/Plenum Publishers.

Nersessian, N. J. (2002). The cognitive basis of model-based reasoning in science. In *The Cognitive Basis of Science*, edited by P. Carruthers, S. Stich and M. Siegal. Cambridge: Cambridge University Press.

Nersessian, N. J. (2005). Interpreting scientific and engineering practices: Integrating the cognitive, social, and cultural dimensions. In M. Gorman, R. D. Tweney, D. Gooding, A. Kincannon (Eds.), *Scientific and Technological Thinking* (pp. 17-56). Hillsdale, NJ: Lawrence Erlbaum.

Nersessian, N. J., Kruz-Milcke, E., Newstetter, W. C., Davies, J. (2003). Research laboratories as evolving distributed cognitive systems. *Proceedings of The 25th Annual Conference of the Cognitive Science Society,* 857-862.

Nersessian, N. J., Newstetter, W., Kurz-Milcke, E., Davies, J. (Authors), (2002). A mixed-method approach to studying distributed cognition in evolving environments. In *Proceedings of the International Conference on Learning Sciences* (pp. 307-314). Hillsdale, NJ: Lawrence Erlbaum Associates.

Pea, R. (1997). Practices of distributed intelligence and designs for education. In G. Salomon (Ed.), *Distributed cognitions: Psychological and educational considerations.* Cambridge: University Press, pp. 47-87.

Prinz, J. J., & Barsalou, L. W. (2000) Steering a course for embodied representation. In E. Dietrich & A. B. Markman (Eds.), *Cognitive dynamics: Conceptual and representational change in humans and machines* (pp.51-77). Mahwah, NJ: Lawrence Erlbaum Associates.

Pylyshyn, Z. (1999). What's in your mind? In E. Lepore, & Z. Pylyshyn (Eds.) (pp. 1-25), *What* *is cognitive science?* London: Blackwell.

Reed, E. (1987). James Gibson's ecological approach to cognition. In A. Costall, A. Still (Eds.), *Cognitive psychology in question.* New York: St. Martin's Press.

Solomon, K. O., Barsalou, L. W. (Authors), (2004). Perceptual simulation in property verification. *Memory and Cognition,* 244-259.

Still, A. W., & Good, J. M. (Authors), (1992). Mutualism in the Human Sciences: Towards the implementation of a theory. *Journal for the Theory of Social Behavior,* 105-128.

Vygotsky, L.S. (1962). *Thought and language.* Cambridge, MA: MIT Press. (Original work published 1934)

Vygotsky, L.S. (1978). *Mind in Society: The development of higher psychological processes.* Cambridge, MA: Harvard University Press.

Wittgenstein, L. (1953). *Philosophical investigations*. (G. Anscombe, Trans.). Oxford: Basil Blackwell.

Yeh, W., & Barsalou, L. W. (Authors), (1996). role of situations in concept learning. In G. W. Cottrell (Ed.), *Proceedings of the Cognitive Science Society* (18th ed., pp. 469-474) Hillsdale, NJ: Lawrence Erlbaum Associates.