The Sounds of Science: Listening to Laboratory Practice

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Works in science and technology studies (STS) have repeatedly pointed to the importance of the visual in scientific practice. STS has also explicated how embodied practice generates scientific knowledge. I aim to supplement this literature by pointing out how sound and hearing are integral aspects of experimentation. Sound helps define how and when lab work is done, and in what kinds of spaces. It structures experimental experience. It affords interactions between researchers and instruments that are richer than could be obtained with vision alone. And it is a site for tacit knowledge, providing a resource for the replication of results, and the transmission of knowledge, and the construction of social boundaries within instrumental communities.

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"Picturing knowledge" has long been a way of speaking in epistemology that has colored the claims of science studies. The "oculocentrism" of mainstream philosophy has been critiqued at least since William James and John Dewey complained of the "mirror theory of knowledge."[1] In contesting traditional views of scientific knowledge, science studies often reproduces this privileging of the visual. Many of the field's terms of art display a clear orientation to looking, gazing, reading, and other things done with the eyes: Latour on "inscriptions" and "drawing things together" (Latour 1988a, 1988b, 1998; Latour and Woolgar 1986), Lynch on "art and artifact" and the "externalized retina" (Lynch 1985a, 1985b, 1988a; Lynch and Edgerton 1988), Rudwick on "visual language" (Rudwick 1976, 1992), Cambrosio

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and Keating on “beautiful pictures” (Cambrosio, Jacobi, and Keating 1993), Shapin and Schaffer on “virtual witnessing” (Shapin and Schaffer 1985), and Galison on “image and logic” (Galison 1997).

The importance of the visual in these works sprang, in part, from an attempt to bring empirical studies of scientific practice to bear on notions in logical empiricism and other strands of philosophy of science relating to “observation” and “sense data” (Boyd 1991a, 1991b; Hacking 1983). Where much analytic philosophy of science emphasized the reduction of knowledge to formal, symbolic terms and relied on decontextualized notions of observation and perception, the new science studies literature described scientific *seeing* as richly rooted in the practices of field and laboratory; it (re)introduced the concept of tacit knowledge, an embodied kind of know-how irreducible to symbolic terms; it highlighted the complex work done by scientific pictures, charts, micrographs, and other “traces”; and it added empirical depth to the claims of Fleck, Wittgenstein, Kuhn, and others that perception (including visual observation) is rooted in “paradigms” and social settings (Collins 1992; Lenoir 1998; Polanyi 1967; Fleck 1979; Wittgenstein 1958; Kuhn 1996).

Although recent works in science and technology studies continue to highlight the visual aspects of scientific practice (Henderson 1999; Kaiser 2000; Latour 1998), nonvisual dimensions have increasingly entered the mix in recent analyses of embodied knowledge, scientific tools, and distributed cognition (Goodwin 1995; Hutchins and Palen 1997; Pinch, Collins, and Carbone 1997). We are beginning to see the material nature of these tools, the ways in which they circulate and become part of embodied work in the field and the lab (Latour 1999). We can discern the whole physical presence of laboratory workers, not just their eyes—how they comport themselves, how they inhabit specially constructed lab spaces, how they interact with instruments and artifacts, how they shape and move their bodies to be perceived and disciplined by the gaze of others, and how their bodily experiences (their illnesses and exertions) are insinuated into their craft (Amann 1994; Francoeur 1997; Hirschauer 1991; Knorr-Cetina 1999; Lawrence 1998; Lynch 1988b; Merz 1998; Ochs, Jacoby, and Gonzales 1994; Rasmussen 1997; Sibum 1995; Thorpe and Shapin 2000).

Along these lines, I want to provide here some remarks—based on an ethnographic and historical study of surface scientists and instrument makers—on how listening, hearing, attuning, and other ear-work are integral to much that goes on in laboratories. Labs are full of sounds and noises, wanted and unwanted, many of which are coordinated with the bodily work of moving through space, looking at specimens, and manipulating instruments. Sounds are fully woven into the knowledge that emerges from experimental practice. What follows in this article is an invitation to practitioners of lab studies to stage performances of John Cage's *4′ 33″* at the sites of scientific work and listen to laboratory practice.[2]

When I talk about examining the sounds of science, my concern is primarily not with those sciences that take acoustic phenomena as their objects of study, their "epistemic things" (Rheinberger 1997)—subspecialties of physics (acoustics, sonoluminescence), medicine and psychology (psychoacoustics), biology (studies of animal songs and communication), engineering (recording and amplification technology), instrumentation (acoustic microscopy, ultrasound), linguistics (phonetics), and computer science (speech-recognition technology). A few sociologists and historians have begun exploring these fields and mapping the epistemological particularities of sound-oriented sciences (Bijsterveld 2001; Brain 1998; Pinch and Trocco 2002; Thompson 1997, 1999; Voskuhl 2004). They have shown, for instance, that the boundary between desirable sound and unwanted noise is very much a constructed, contingent, and historically variable one. They show that sound and space are inextricable and that communally held views on the proper nature of sound help shape how architectural and public space is engineered, constructed, and experienced. These authors show how the lived experience of the experimental subject gives rise to contextually specific notions of what sounds are worth investigating and how to capture the world of sound in the abstracted languages of science. And finally, they describe how auditory phenomena are often important ingredients in the debates about similarity, difference, and family resemblance that typify scientific and technological controversies.

In what follows, I hope to show that auditory phenomena have similar epistemological consequences even in laboratory contexts where they are not the primary objects of study. I open with an examination of the sometimes undesirable effects of laboratory sounds. Noise can shake and disturb laboratory tools and personnel, and, as a consequence, auditory concerns shape much of the when and where of experimentation. By being aware of the sound environment, science studies can gain new insights into the ways experimental spaces are constituted. Next, I describe some of the sounds produced and/or attended to by surface scientists and the ways these are folded into experimental practice. I attempt to show that sound is an integral (if often overlooked) ingredient in tacit knowledge. Surface scientists carefully manage auditory (as well as visual and haptic) cues to liberate different kinds of information from their experiments. And finally, these same surface scientists call on their audience's personal auditory (and other sensory) experience to more powerfully convey their ideas.

The empirical material of this study was drawn from three years of ethnographic and interview work with researchers and engineers working in and around materials science and surface science.[3] Some are graduate students, undergraduates, and professors working in research labs; others (architectural consultants and safety inspectors) construct and inspect experimental spaces; and yet others design, manufacture, and oversee scientific instruments, particularly transmission electron microscopes (TEMs) and scanning probe microscopes (SPMs). I refer those interested in my ethnographic methods to an earlier article on cleanliness and contamination in materials science and surface science (Mody 2001). There, I outlined some of the actors who come together in these experimental settings, and the ways their differing ideas about contamination are progressively negotiated and (occasionally) harmonized.

Sound as Contaminant

It is no coincidence that looking at experimental practices of understanding, containing, and even co-opting contamination leads in turn to an investigation of laboratory sounds since auditory phenomena—along with heat, light, dust, oil, air, water vapor, dander, and so on—are an important source of contamination in experimental surface science:

> If we look at . . . manufacturing microelectronics . . . a lot of these processes are very very sensitive to both vibration and noise. . . . [I]f you shine noise, sound, at many of these tools, that also makes them shake, because sound is just a fluctuating pressure in the atmosphere and that fluctuating pressure will act on the structure of the machine or the tool to make it shake. So both sound and vibration are what we generally classify as contaminants. When people are doing measurements in laboratories . . . they're using tools that are sensitive to all sorts of contamination—particulates in the atmosphere . . . temperature fluctuations . . . humidity can affect the measurements, and so can vibration and noise. So the whole class of physical phenomena can be grouped under the name contamination. (Interview with Colin Gordon, acoustical consultant, Colin Gordon Associates, March 12, 2001)[4]

Gordon is a leading consultant to architectural firms specializing in the building of laboratories, clean rooms, and semiconductor manufacturing plants. As this quote hints, his life's work is to help shape these spaces to minimize sounds that can disrupt the functioning of labs and fabrication facilities.

Many general observations from anthropological studies of pollution ritual (most notably Mary Douglas's 1966 celebrated *Purity and Danger*) hold true in analyzing noise, sound, and vibration as contaminants.[5] For instance, the nature of pollution is momentary and contingent. Although many in surface science project a rhetoric of high cleanliness and purity, the patchwork of experimental life means that what counts as pollution one minute might be a key ingredient or tool (or side effect thereof) the next. In nanofabrication facilities and other clean rooms (which the semiconductor industry claims are the cleanest places on Earth), for example, fans and ductwork cover most of the ceiling, pulling away the minute particles of dust that might ruin semiconductor processing; at the same time, these fans create an intense racket that makes it difficult for technicians to communicate with each other, endangers their health, and rattles the instruments used to inspect semiconductor materials.

Also, sound acts as what might be called an *even though* filter—that is, an experiment that works even though some potential dirt is present is taken to be more powerful than an experiment that works only in the absence of contamination. In the early 1980s, for instance, when scanning tunneling microscopy (STM) was still an unproven technique, many of the first STMs were initially constructed in noisy, unpromising locations (often near elevators shafts), until they had achieved an important milestone (such as atomic resolution) and could therefore be seen as viable instruments and moved to some lab with fewer ambient sounds.[6] Even today, probe microscopists most often run their instruments with laboratory doors open and with air conditioners and other sources of noise running. If a feature can be seen with the microscope despite these auditory contaminants, then it is probably real—and if it appears to be both real and interesting, then the microscopist will often close the doors and turn off the pumps to peer at it more closely.

Auditory contamination shapes experimental life in a variety of ways. The human body, for instance, can be both a source and a sink for various contaminating sounds. There is an intricate care of the self needed for operating many laboratory instruments so as not to produce perturbing noises (Knorr-Cetina 1996). In transmission electron microscopy, for instance, those in the TEM room must constantly be aware of their bodily habitus—how they position themselves, when they address each other, how they move—so as not to produce sounds or vibrations that might disturb the instrument by talking too loudly at the wrong time or accidentally bumping the microscope console. This is particularly true during the taking of micrographs, when air conditioners and pumps and even telephones may be temporarily turned off. In probe microscopy, habitus is usually more casual, although the effects of sound on the instrument are more directly perceived—a clap or other sharp noise can immediately be seen as a streak on the scan, and conversation can be seen as a trace in an oscilloscope measuring the movement of the probe.

At the same time, experimental sounds have complex effects on the experience of laboratory life. TEMs run best with the lights off and a minimum of noise from both experimenters and apparatus, so that maintaining this proper self-discipline can be quite tiring. Researchers often emerge from a microscope run bleary-eyed, and instrument managers occasionally find students asleep in front of the microscope. This is particularly the case since human traffic within and around the laboratory can be a major source of contaminating sounds—thus, many experiments involving sensitive instruments take place at night, or in special locations away from the main lab building. Take, for instance, this story from the early days of STM, in which worries about noise and vibration funneled experimental work into unusual places and times:

> We decided we were going to try this on a Sunday morning, it was nice working nights and weekends because it was very quiet in the building. So on a Sunday morning, I'd be, you know, we were tunneling, we could see that it worked because every scan you could see those I-V curves dance up and down. . . . [B]ecause it was just too noisy, you could really only do experiments in the evenings and on the weekends. Right, so we would work for a couple days, [creating] software, trying to get analysis stuff ready and analyze data that we had, and then we'd go into a streak where we just worked nights and get data. And of course everybody was struggling with that, at Bell Labs they had built a special building to do their STM in because they couldn't live in their main building, it was too noisy, and we worked at night, at Cambridge, they built a special environmental room with big, you know, foam-padded walls and everything to do the—if you see these instruments now, right, you can plunk them on the table here and it works just fine. But it was very different then because we, you were really just learning and discovering how to do this stuff. (Interview with Ruud Tromp, an early STM researcher at a corporate laboratory, February 23, 2001)

Sound and Space

Many procedures in surface science (such as characterizing specimens with a probe microscope) require close attention over very long periods of time, often alone and at night, resulting in extreme tedium. While the eyes are engaged in monitoring instruments, auditory phenomena can be important in circumventing boredom. Consequently, conversation and music are much more pervasive phenomena in labs than has been noticed in the lab studies literature. Many labs have a radio or stereo and a large stack of CDs and tapes (where the authority to choose and play music usually rests with the graduate students, postdocs, and technicians who occupy the lab most of the time, rather than with the head of the lab group). At the same time, music and conversation may be seen as interfering with experimental results (one woman told me she plays music in her lab continuously, but when she encounters a problem with her microscope and calls the manufacturer, the company's support staff immediately ask her if she has a stereo on—suppressing sounds is a routine first step in clearing up problems with some instruments).

Auditory phenomena can be noxious for people as well as instruments, both inside and outside the lab. Clean rooms, for example, can be extremely uncomfortable, in part because of ambient noise levels. Much lab equipment produces dangerous amounts of noise, some continuously and some only on occasion. Like other contaminants, such noises are part of the checklist for local Environmental Health and Safety inspectors. With clean rooms, such "nuisance noise" comes about because of the great amount of work needed to construct a space in which the epistemic things of surface science (which often have dimensions of only a few nanometers or even angstroms) can be protected both from the dirt exuded by experimental bodies and the pollution oozing in from an ostensibly hostile and contaminating outside world.[7]

At the same time, threatening sounds travel both ways; the hard work of crafting a clean laboratory space creates many sounds and other contaminants that can pollute the lab's surroundings. Moreover, the boundary between lab and world always remains somewhat flexible and contestable, where sound environments both constrain and enable this ambiguity. The chemicals used in cleaning and manufacturing the specialized tools and materials of surface chemistry, for instance, have to leave the laboratory and be disposed of. The way this is done results in the characteristic droning sound of many high-tech outdoor spaces. One professor described for me the problems of forcing waste chemicals out of labs through rooftop vents, while avoiding noise pollution:

> You've got exhaust fans on the room which try to launch the air out of there, you don't just let the exhaust drift up and move off. You want to shoot it up and get it high so that when it finally comes down to the ground, if it comes down at all, it's way diffused and spread over miles. But when fans really kick out exhaust with high velocity, they sound like jet engines up on the roof. . . . [A]ll those wet labs, you hear the bzzzzzzz running all the time. And we're a little concerned that when you get a lot more of those, it would be possible you get the whole quad where you get this constant, unacceptable drone. (Interview with an academic electrical engineer, faculty consultant for construction of new clean room facility, April 25, 2000)

That sound and space, particularly built space, are bound up in interesting ways is one of the first observations of any phenomenology of sound (Ihde

1976, 60; Sterne 1997). There is, of course, an already-burgeoning literature on place, built environment, and science (Knowles and Leslie 2001; Lynch 1991; Schaffer 1998; Shapin 1988). This literature aims to show how scientific spaces are designed and engineered; how particular kinds of behavior and social organization flow through those spaces; and how the particular kinds of knowledge produced in those spaces is afforded by, and reflective of, their constitution. With the exception of the studies by Karin Bijsterveld (2001) and Emily Thompson (1997, 1999), however, this literature has paid relatively little attention to issues of sound. For the participants in laboratory design, though, such issues are often present and occasionally they become urgent. Indeed, a subindustry of acoustical consultants has arisen over the past thirty years dedicated to helping teams of architects and engineers work around issues of sound, making sure the right kinds of sound stay in the lab, while contaminating ones are kept out.

The construction and maintenance of laboratory spaces can itself generate unwanted sounds. The heavy machinery and occasional drilling and explosions that attend the building of labs (and other structures around them) produce noises that limit the lengths of some experiments and the times of day when they can be conducted. The in-and-out of traffic and deliveries, and even the footfalls of people walking around laboratory buildings, also generate disturbing sounds that vary throughout the day and week. But experimenters show remarkable resourcefulness about space and often redraw the line between lab and nonlab so that they can conduct experiments in more suitable sound environments. The following is a story about the flexibility of space in the early days of STM:

> Yeah, we moved to the ground floor at some point because it was just too noisy up here, right. You know, the elevator's right back there, and it's a big freight elevator that goes up and down all day. Yeah, at some point, CSS, you know where the big CSS electronics shop used to be? Sort of underneath the garden in the back. They got new space, and so they moved out and we squatted there for a while. It was this huge space, you know, this enormous lab, and we just occupied a tiny little corner in there and we did a bunch of good experiments. And then at some point, we were kicked out of there. And so we found an empty office on Aisle 1. This was all pretty informal. And so one night, you know, we had spotted this empty office so we took all our stuff, our STM, you know, which was on casters, and the electronics, and we just, at night we wheeled it to the back lab and we started squatting in that office. And the office actually is, it never got converted back to an office again, it became our lab. And there's still an STM there today. So, yeah, so it was, but ground floor was important because you know you're on bedrock there so it's a lot more stable than being up here is. (Interview with Tromp, February 23, 2001)

The same scrounging of space continues today, as evidenced by this recent advice on how to deal with noise problems in setting up modern probe microscopes:

> We have a Nanoscope [a kind of scanning probe microscope] on the seventh floor of a steel-framed building and have had some vibration problems also. For what it's worth, here are some things that worked for us:
>
> 1. Acoustic noises caused by the ventilation system were a big problem. Finally, we moved the instrument from the lab to an office that had less air flow and a quieter duct system, and lined the office cum lab with Sonex foam. It's now like an anechoic chamber and you can hear your heart beat. (Posting to an e-mail listserv for scanning probe microscope users, November 26, 1995)

There are many strategies like these for protecting scanning probe microscopes from vibrations and acoustic noise. One possibility is to buy acoustic hoods and vibration isolation tables from manufacturers. Many researchers, though, choose to cobble solutions from materials found at hardware stores or garage sales. A perusal of an e-mail forum dedicated to these instruments yields some of the following vibration isolation equipment: pails of sand; blank headstones; disused refrigerators; old acoustic hoods for noisy dot-matrix printers; inner tubes; and, probably the most popular, bungee cords or surgical tubing, used to hang the microscope from the ceiling or a stand or even the legs of an upturned table.[8]

One quality that many probe microscopists desire in such vibration isolation systems is portability. As Bruno Latour has made clear, one crucial way to enroll allies and win scientific controversies is to transform more and more bits of the world into laboratories, to make the epistemic things of a discipline hard enough, and the world gentle enough, for them to survive outside the confines of the lab (Latour 1988c). One part of this is making sure the world sounds like the lab. Not doing so can lead to trouble. For instance, an instrument designed and developed in one place may unexpectedly fail to work if the premises of the company that buys it do not sound like those of the company that manufactured it:

> People like LMB and MatterTech, the major manufacturers of the tools that we use would develop the tool in their own laboratory . . . typically their laboratory would be on a slab on grade floor [where the effects of sound and vibration can be minimized]. . . . And you'd get all the bits and pieces and put a tool together and get it to work in the laboratory and then deliver it to Beltronix and much to Beltronix's surprise and their surprise, it wouldn't work because Beltronix' floor was on the second story or the third story of a building [where the effects of sound and vibration are a bigger problem]. (Interview with Gordon, March 12, 2001)

Another arena in which sound affects the ability to move instruments out of the lab is the world of conference trade shows, where instrument manufacturers and potential customers mingle noisily in crowded and acoustically suspect places such as gymnasiums, cafeterias, and hotel ballrooms. It is a crucial advantage for a manufacturer to have a working instrument in his or her booth to show to interested researchers. Yet the trade show environment sounds quite unlike the lab. Instruments and vibration isolation systems that are portable enough and robust enough to work at trade shows are highly prized.

One way to avoid noise pollution is to move the lab to quiet, suburban locales far away from the noisy bustling of academic campuses and industrial research parks. Today's probe microscopes are small enough and cheap enough that manufacturer's applications labs and independent surface analysis companies can be set up almost anywhere. Quite often, these small laboratories spring up in comfortable and quiet locations: abandoned naval air stations, deeply rural New Jersey hamlets, ski chalets in Lake Tahoe resort towns, and homes in the suburbs of midwestern metropolises. To turn Bruno Latour's famous phrase on its head, "give me a suburb and I will raise the world" (Latour 1983). That is, although Latour is right in pointing out that laboratories can be expensive and powerful tools in winning technoscientific arguments, the lab is not an ultimately stable construct. Scientists and technicians are adept at cobbling resources to constitute laboratories in seemingly unlikely places. What counts as a laboratory space is highly context-dependent, and often it is the soundscape of a place that shapes what knowledge can be created there.

Sound Effects

Let us consider what sounds inhabit the spaces of surface science and how and when they become relevant. The task of preparing and maintaining the epistemic materials of surface science, and of bringing them under the disciplining gaze of instruments such as microscopes, diffractometers, and spectroscopes, is mechanically complex and noisy. Pipes bring in and take away gurgling water; spray cans of compressed air blow dust away; sonicators shake off contaminants; refrigerators chill acids and other chemicals; centrifuges whirl specimens around; and fume hoods siphon off dangerous gases. Vacuum pumps, especially, abound in these labs, preserving uncontaminated environments where metals and semiconductors will not oxidize. Many of the most fundamental techniques of surface science (electron microscopy, low-energy electron diffraction, mass spectrometry) require some sort of vacuum, often an ultrahigh vacuum, to work. Thus, vacuum pumps provide a constant background hum in many surface science laboratories. These pumps, though, can also shake and disrupt instruments and interfere with experiments.

Other sounds are only indirectly associated with the preparation of materials. Carts push equipment (often large, heavy bottles of compressed gas) through hallways; timers alert lab workers when to begin the next step of an experiment; radios play; people talk; and doors ("many of which are heavy, spring-loaded, self-closing doors") slam shut.[9] One particularly loud and often disruptive (although vital) set of sounds is heavy machinery (drills, lathes, grinders) used for making experimental apparatus. Many academic departments and research labs have associated machine shops where tools and equipment are manufactured or tinkered with. Often, machine shops are located in the center of a complex of lab rooms, and the occasional buzzing and shrieking of these tools can be heard throughout the experimental day. When using some characterization instruments, especially probe or electron microscopes, these sounds can be directly seen as streaks in images that correspond to the starting of a grinder or a press.

Other sounds stem from the need to preserve experimental bodies as well as experimental materials. Air conditioners run constantly since many lab spaces have no windows (and open windows are discouraged anyway because they let in dust and other contaminants). In TEM labs, air conditioners are often turned off just when a micrograph is being recorded, so that the inscriptions produced by the microscope are less contaminated by the sound of the air conditioning pumps. Fans for computer processors, and the sound of keyboards, typewriters, copiers, and telephones are also audible in many parts of lab buildings. Interestingly, for at least one TEM lab I saw, there was a telephone present in the microscopy room, but its ringer was turned off so that the operation of the microscope would not be impaired. Finally, various alarms are needed in any building that contains dangerous machinery and chemicals. The sound of these alarms has to be carefully coordinated—if a very alarming klaxon is used for only a small, localized danger, unnecessary disruption will occur. On the other hand, not enough people will respond to a widespread hazard if an alarm is too quiet and local. In many cases, different levels of alarm sounds must be used.[10]

Sound Knowledge

The list above is by no means exhaustive, but it lets us ask a more compelling question: do sounds merely surround knowledge making in labs, or are they also bound up in the knowledge that gets made? It should be clear that sound helps lend structure to experiments—where they are done, when they are done, what they look like. But is it epistemologically relevant that the rich visual world described in early laboratory studies (the world of inscriptions, diagrams, golden images, and so forth) is imbued with sound?

In asking these questions, we move from confronting sound-as-contaminant to sound-as-experimental-cue. In surface science, where the entities of interest can be of atomic (or even subatomic) dimension, any stray dirt, radiation, or vibration can be disastrous. Yet experimenters are often able to co-opt these same contaminating noises to yield new kinds of data about apparatus and phenomena. If stray sounds are deleterious to an instrument, then, as we shall see, more controlled sounds (e.g., the human voice) can be useful in its diagnosis or operation. And even contaminating sounds can be richly instructive. The line between disrupting sounds and enabling ones has to be negotiated moment by moment.

Certainly, the soundscape of the lab is important in the accruing of tacit knowledge.[11] Many instruments in surface science and materials science have parts and mechanisms that make specific sounds—the whirr of micrograph plates being moved inside a TEM, the chuk-chuk of a probe being lowered on an atomic force microscope (AFM), the sproing and click of a coil being shoved into place on a microprobe.[12] When things run smoothly, these sounds unfold regularly, marking out the running of a clean experiment. Learning these sounds, and the experimental rhythm they indicate, is part of learning the proper use of the instrument. Many TEMs and home-built STMs resemble organ consoles, with a variety of knobs and dials and visual readouts spread before the operator. Instrument users often coordinate visual and auditory cues to manage the variety of information before them. The tacit knowledge of such sounds is difficult to pass on from one operator to another and usually comes only with long experience with the instrument. With such experience also comes the tacit knowledge of the sounds made when tools are not operating smoothly. Much of the machinery associated with instruments such as TEMs and vacuum chambers is balanced to minimize the background noise it produces. Attending to changes in this background can tell an experienced operator that something is wrong. Furthermore, such sounds can be used to diagnose problems, particularly with mechanisms hidden inside the instrument.

One instrument that both emits and measures lab sounds is the experimenter's body. Diagnosing problems with microscopes and other tools can involve not only listening for sounds but also producing them and watching their effect. Sometimes this involves highly idiosyncratic practices. One informant told me that she sings to the spectrometers in her lab when they are not working, and that, depending on the choice of song, this often seems to help. This resembles the local practices Kathleen Jordan and Mike Lynch found among plasmid prep technicians, where the "translucent box" of the technique was continually open to local reinterpretation through informal recipes, tricks, and superstitions (Jordan and Lynch 1992). Like the practices Jordan and Lynch observed, singing has its informal yet technical rationale—my informant claimed that singing may slightly warm the air near the instrument, improving performance.

In probe microscopy, the use of singing, talking, and other embodied sounds has a long history for diagnosing problems:

> We're on a noisy floor, so we had plenty of noise problems. I remember Henri Piper [co-inventor of STM] at one point walking into the lab while we were struggling, and . . . he has this big booming voice, and so he walked into the lab and saw the tunneling trace in the oscilloscope which was, you know, dancing up and down as he was talking, and he was telling us "guys, you still have a problem." (Interview with Tromp, February 23, 2001)

> It was amazing. Literally at times you know we wondered if there were acoustic vibrations that were hitting so literally you'd see people trying to sing to the microscope. Just, you know, looking at an oscilloscope seeing that if they hit a certain note it excited a resonant frequency in the acoustic spectra—if they could see that in the noise on the oscilloscope. (Interview with Fred Leibsle, academic surface scientist, describing experiences building STMs as a graduate student, January 1, 2001; emphasis in original conversation)

> Acoustic noise is the next issue to consider. . . . [Getting rid of it] can be fun. It can also be frustrating. Again, only do what you need to do. Look around for easy solutions. If there is other equipment around, try turning it off. If you have more than one choice of location, try them all. Clap your hands and stomp your feet to see what noise is your enemy (Your coworkers will forget by next week). (Posting to an email listserv for scanning probe microscope users, February 9, 2000)

As this last quote indicates, stomping and clapping are common ways of testing the acoustic isolation of probe microscopes because the short, sharp sound of the clap shows up readily on the visual output of the instrument. When I visited one STM lab, the head of the group ran into the room housing the microscope while his technician and I watched the visual output in the next room—we could hear him clapping and stomping, and then he ran around to us and shouted "Did you see me? Is that me?" pointing to a streak on the STM image. Often when researchers demonstrate their microscopes they clap or rap on a table to show that something is really going on, indexical proof that the instrument is churning away and is sensitive enough to be disturbed by such sounds.

Another index of the microscope's operation comes from reversing the flow of sound. Some STM and AFM researchers and designers convert the output of the instrument into an auditory signal and listen to it scanning at the same time they watch it form an image. There are a number of rationales given for this. Some instrumental breakdowns, it is claimed, are more easily heard than seen—a crashing tip, for instance, makes a loud, distinct sound (when audibilized in this way) that is less easily noted in the visual output. Operators of these instruments gain tacit knowledge about what certain sounds mean and develop an aesthetic relationship to these acoustic indicators (just as most microscopists also develop an aesthetic sensibility about the images they see). In particular, some operators describe listening to the microscope as bringing them more in tune with its operation:

> You can listen to periodicity much better than seeing. You can hear it, than seeing. And he got also some feeling for the measurement. It's really a little bit mystic, but he could say, "Well, if I hear it, it sounds like this, then I know that it is now really at the best resolution." (Interview with Robert Sum, probe microscope designer, describing a colleague from graduate school, November 9, 2001)

> Your ear learns very quickly and you can tell what, where you are. It gives you much more sense of being in the system as soon as you have your ears involved. (Interview with an STM researcher at a corporate lab, November 12, 2001)

Various ostensibly technical reasons for using sound this way run alongside the aesthetic ones—the ears, it is said, are an extra channel for information, a logarithmic sensor that can process certain kinds of data better than the eyes can. But also, listening to the microscope is felt to increase embodied interaction with the instrument, giving more room for experimental hands or *Fingerspitzengefühl*. The experimenters who choose to audibilize their microscope's output are often those that build their own STMs or AFMs. These same experimenters usually include various knobs and dials and analog controls on their microscopes, rather than just the digital computer controls found on most commercial instruments. Both the analog controls and the audibilized output are seen as offering a richer play for the experimenter's body in operating the instrument:

> **Interviewee:** We are analog guys. . . . [T]his feeling of having in your hand what you do, is with an analog knob much better than if you type in "current should

> trace from 500 picoamperes to 503 picoamperes." . . . This is different to having between your fingers, the feeling of making this tip go a little bit further or a little back or shaking the tip a little bit. You have a much more direct link to what you're doing. You . . . are part of this setup, as the human being, as being the operator of these knobs. . . . You have more senses if you do it this way.
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> **Mody:** Were you listening to the output as well?
>
> **Interviewee:** Yes, of course. . . . [T]his is a second conscious channel which is complementary to eyes, is the ear, and the ear is a logarithmic instrument. . . . [W]e always have a loudspeaker there, which all the time is wooshhh, and you get practice. I mean, if you're sitting hours and hours, Uli [a very early STM researcher] will tell me "Oh, did you hear that, I think some"—not even looking at the screen. "You should a little bit move this and then go to where it sounds better." Then we go to where it sounds better and all of a sudden, mysteriously, it's still a mystery in a sense, these molecules shine up. (Interview with an academic surface scientist, November 14, 2001)

Thus, many of those who choose to build their own probe microscopes orient positively to embodied knowledge, in all its mystic and aesthetic aspects; for these researchers, sound facilitates the acquisition of knowledge, precisely because of its aesthetic qualities. At the same time, aesthetics is an important boundary-drawing tool for instrument builders. Scientists and engineers who make their own instruments, or who design them for others, are today a small minority in the probe microscopy community. Aestheticizing the operation or output of their microscopes imbues their work with a kind of craft status, justifying the difficult work of building an instrument, and separating their research from that of the majority who run mass-produced commercial instruments (and who rarely listen to their microscopes).

Thus, audibilizing the output of the probe produces sounds that are "beautiful," "cool," "neat"—in one case, I even heard them described as "ugly" in the same manner as avant-garde music. As this quote shows, such sounds are readily seen as intriguing, but their utility is more ambiguous:

> You just take what looks at the time like a bunch of noise and transform it—you can see the spectrum. It turns out that for the cantilevers we use, that all happens sort of below 20 kHz, so you can actually listen to it. It's kind of neat. I mean, as you approach this surface, you get damping effects happening between the tip and the surface, so the spectrum will shift and you can shoop [rising noise] shoop [falling noise], so as you pull up and down, if you don't have anything tethered to it, it actually sounds kind of like a wave crashing on shore with the shift of the frequencies, the emphasis sort of moves in the spectrum. It's kind of interesting. And then as you pull things you can hear, as the domain pops open you can hear the domain snap, it gives a little popping sound or a crackling sound. . . . Clint . . . uses the headphones to track down these problems of getting around quantization issues in the software. In terms of

> actual science, I don't know that anybody's done any science using the headphones. I think mostly it's just a diagnostic tool. Maybe a sanity check. And it's fun to listen to, it's actually pretty neat. (Interview with Dan Bocek, probe microscope designer, March 23, 2001)

Yet as is amply demonstrated in the science studies literature on images, diagrams, and other visual material, appeals to aesthetics in science are usually bound up with the pragmatic details of knowledge making. The sounds of the microscope may be "cool" or "mystical," but it is difficult to sort the aesthetic appeal of these sounds from their ability to help solve particular experimental problems. The same microscope can be tinkered with to appeal to—and provide cues for—different senses (visual, auditory, and haptic outputs are all used), so that different kinds of sensory experience satisfy different experimental ends. Listening is most important for tasks where the instrument must be monitored or manipulated in some way over time. Operators orient to sound's temporal aspects in such cases. When the temporal is downplayed, as for example in the creation of static images that can be printed out, published, and circulated, the visual becomes primary. Even for some dynamic processes, sound fades into the background—for instance, when the microscope is running smoothly and automatically, operators usually orient more to changes in the visual field than the auditory.[13] Indeed, laboratory workers are keenly aware of which senses serve them best for which tasks. When, for example, surface scientists put different kinds of molecules down onto a substrate and watch them diffuse or react with each other, they use videotapes to record the reactions, often playing these recordings later for other lab workers or during conference presentations. Even here, though, sound provides cues for understanding—during the recording of these tapes, it is common to hook up a microphone and describe what is being seen and done, so that later viewers will be able to see the microscope image and hear a narrative of its creation and match changes in the visual field with the drama of the storytelling:

> There was this . . . video-frame-capture technology and it would take inputs like this and then go through one of Heinrich Liechti's [a postdoc] magic boxes and then appear, you know, on a TV monitor and get saved to videotape. And it was sort of a live feed to videotape and in fact we would hook the audio in and we would narrate as we were capturing these images. We would say, "OK, we're doing AFM in fluid, we've got fibrinogen on mica, and now we're going to inject the, you know, blah blah blah to polymerize the fibrinogen and OH MY GOD LOOK AT THAT, IT'S POLYMERIZING!" And then we would have other people in the lab who later would wear these headphones and play back the tape and there was this video transfer module that could then transfer

> one frame off to a computer, and so they'd sit there and wait 'till they heard the "Oh my God" and hit Enter and transfer the picture over. (Interview with Craig Prater, probe microscope designer, describing graduate school experiences March 19, 2001; emphasis in original interview)

Many sciences dealing with phenomena that occur at audible frequencies transform their data into acoustic signals.[14] While researchers usually describe these translations as adding nothing scientific, it is notable that they are taken to be more publicly convincing than verbal explanations. STM researchers, for instance, sometimes play tapes of their microscopes scanning an array of atoms as background noise throughout their talks, and report that this is an easy way to get audiences excited and interested. One AFM designer told me how sound can seem to offer more unmediated access to the workings of the instrument, particularly in settings such as trade shows where potential customers need to be quickly offered a glimpse of the instrument's capabilities:

> It's actually really good at [trade] shows too, because if you're introducing the subject to somebody—thermal noise for example, it's one thing to explain it to them, it's another to hand them a pair of headphones and say, "Look, this is what thermal noise is." You can explain the concept of damping and things like how the spectrum shifts because it's just totally obvious when you just hear it, it's like, "Yeah, of course, that's what's happening." (Interview with Dan Bocek, March 23, 2001)

This raises a few final points about the uses of audibilization. As Emily Thompson and Robert Brain have pointed out, in sciences where sound is an object of study, the struggle for more than a century has been to turn informative sounds into readable inscriptions (Brain 1998; Thompson 1997, 1999). As Karin Knorr-Cetina (1999) has noted, the senses play a diminished role in today's experimental (particularly laboratory) sciences. A whole host of tools and instruments intercede between the experimenter and the specimen being studied; these instruments transform the feel, sound, taste, smell, and look of the sample (as well as other properties) into new (usually visual) qualities that can then be packaged into Latourian immutable mobiles (diagrams, graphs, charts, etc.). In none of the examples I have given so far is it the sound of an actual surface that is of interest to the surface science. Rather, they attend to the sounds of buildings or people or instruments. As I have tried to show, sound is vitally important in giving experimenters access to information about the tools and instruments that mediate between them and the materials they study. As such, sound is often a site for local, tacit knowledge. But I have also tried to show ways in which sound is public and communal, and therefore the grounds for forging shared knowledge. We should not assume that only visual inscriptions are public. Sound surrounds all of us, and for hearing experimentalists it is a matter of everyday, embodied experience. By using sound to communicate knowledge, researchers appeal to audience members' personal, tacit, embodied experience, which is seen as making formal knowledge more easily understood. Listening to an AFM image is thought of as putting the listener in the surface being scanned, in much the same way that three-dimensional rendering software is used to give images in which the viewer's perspective is that of someone walking on a nanometer-scale surface.[15]

The translation of information into sound and the appeal to auditory experience is not restricted to listening to instruments. Auditory experience is personal yet common, so that framing explanations in terms of acoustic phenomena can be a powerful bridge for transferring knowledge. In areas of physics and engineering that deal with periodic or wave phenomena, explanations are commonly framed in terms of sounds that the audience may have experienced. Probe microscopes (particularly AFM), for example, are frequently compared to the phonograph, and their images likened to the sounds of vinyl records (Anonymous 1992). In public presentations, researchers often draw on sound as an explanatory resource. For instance, at a recent probe microscopy conference, I saw a speaker trying to explain the difference between imaging with a hard and a soft cantilever in AFM—to do so, he showed the audience a gong and asked them to imagine that it was a surface being imaged. He struck the gong with the soft end of a mallet, and then again with the wooden handle of the mallet, and asked the audience to listen to the difference in the sounds produced and imagine the different ringings of the gong as similar to the different interactions between a surface and a hard or soft probe.

In general, the talk of probe microscopists is saturated with uses of sound as a metaphorical resource in relating technical information—they refer to cantilevers ringing, they measure deflections with tuning forks, and they amplify signals to reduce noise. The role of gesture and other visually oriented interaction (such as impromptu diagramming) is well-known in discussions of scientific communication (Goodwin 1994, 1996; Ochs, Gonzales, and Jacoby 1996; Ochs, Jacoby, and Gonzales 1994). But little has been written concerning auditory equivalents, even though much of the talk of scientists is riddled with appeals to sound as a metaphor, and imitations of the sounds of instruments and equipment.

Conclusion

Sound, then, is pervasive in laboratory life and impinges on experimental experience in surprising and often epistemologically significant ways. What this should point to, I hope, is the need for a fuller understanding of what *embodied knowledge* might entail. We have seen how this one aspect of embodiment—sound and hearing—is implicated in the metaphors scientists use; the spaces they design, build, and work in; and the ways they pass the time, communicate with each other and their publics, mark out social roles, diagnose technical problems, perform experimental rituals, and use instruments and experiments to create knowledge.

I conclude with some recommendations for further work. On one hand, I would highlight the intrinsic importance of sound. As I have shown, sound and noise are frequently actors' categories; while this study has been limited to experimental surface science (and some allied fields), I would expect many findings to extend to other experimental settings. I would also expect, however, that other sciences would use sound in quite different ways, and I hope that future studies will investigate the diverse meanings of the auditory. At the same time, sound has features that make it a powerful analysts' category. For instance, sound fills and demarcates space, so that studies of the social construction of experimental places would do well to listen to the experimental soundscape; as we have seen, the auditory approach aids in deconstructing the distinction between the inside and outside of the lab, and in demonstrating the malleability of scientific space. Also, sound extends over time, and constructions of time have long been of interest to lab studies (Traweek 1988). Listening to laboratory practice gives a good entrée to understanding the microscale constructions of time in science. In conjunction, sound has an immediacy (Jakobson 1990) that allows it to powerfully convey meaning and context; while many lab studies open with an ethnographic description of the laboratory, these are almost always visual descriptions that neglect much of the sensible setting of ethnography.[16] By keeping our ears open and writing the sounds of science into our texts, laboratory ethnographers can convey even more of the richness of experimental life and bring readers closer to the worlds being described.

My second recommendation is to take sound as one of many sites for exploring concerns in science studies, particularly issues of situated and embodied knowledge. One motivation for talking about embodied or tacit knowledge is that it varies (from person to person, lab to lab, discipline to discipline) but in hidden and often problematic ways (where variability can contradict invariant and universal scientific truth claims). At the same time, the presumed commonality of much embodied experience is used as a resource (for instance, in conveying abstract ideas by appeal to gestural or auditory metaphors). Examining hearing and the other senses can focus attention on these issues. How, for example, does embodied knowledge vary with the body in question? One lacuna of this piece is that I have not confronted the experience of deaf and hard-of-hearing scientists. What are the epistemological particularities of deaf and hard-of-hearing experimenters? What is their experience of laboratory life? We know that many well-known scientists and technologists have been or became deaf, but we have as yet little understanding of what that meant for their practices and the knowledge they produced. And what of the other senses? How, for example, do different disciplines draw on different kinds of sensation? Geology, for one, is famous for its use of taste, and medicine and chemistry often deal with smell. After all, chemical work can resemble a quotidian activity—cooking—in which smell and taste are important, and many specimen preparation techniques are referred to as *recipes*. Science studies has yet to track these variations and give them a thick description, however. When it does, we shall understand better how scientific knowledge is forged by all the senses, and how all experimental sense data—taste, touch, hearing, and smell, as well as sight—are ineluctably cultural products.

NOTES

1. See Rorty (1979, Introduction and 259-305) for a description of James and Dewey's position. See also the contributions to Levin (1993), many of which argue that Western culture privileges the visual and that the gaze provides the channel for power and desire in ways that constitute modern subjectivity.

2. Cage's most notorious piece (a "silent" work in which the pianist performs a recital without playing any notes) was an attempt to break the frame of art and incite audiences to notice the visual, auditory, and embodied context surrounding performances.

3. Relatively little has been written about surface science or materials science in STS. See Groenewegen and Peters (2002), Hessenbruch (2004), Hoddeson (1992), and Leslie (1993).

4. Where requested by interviewees, places and personal and corporate names are pseudonyms or have been elided.

5. Anthony Jackson (1968), referencing Mary Douglas's (1966) work on pollution, puts it well: "Noise or unpatterned sounds reflect uncontrolled situations or transitional states or threats to the patterned social order" (p. 295).

6. Scanning probe microscopes (SPMs) work by bringing a small solid probe very close (to within the diameter of an atom) to a surface and measuring a variety of interactions between probe and surface. The probe is scanned over the surface, and measurements of the interactions at

each point are converted into pixels in an image, giving a picture of (something like) the topography of the surface. Sound and vibration disrupt SPMs by displacing the probe relative to the surface in an uncontrolled manner, thereby blurring or streaking the image. The scanning tunneling microscope (STM), invented around 1982, and the atomic force microscope (AFM), invented in 1986, are the two most common SPMs. See Hessenbruch (2001) for some background on the history of probe microscopy.

7. The term *nuisance noise* comes from a personal communication from TS, August 6, 2001, an Environmental Health and Safety officer at Cornell.

8. A good example of scientific bricolage. See Knorr-Cetina (1981, 34).

9. Quote is from TS (August 6, 2001, personal communication). I owe much of this section to TS.

10. Again, thanks to TS. Also, thanks to Bob Crease for pointing out this phenomenon.

11. I rely on the Collins version of tacit knowledge here. For Collins's latest statement on the subject, see Collins (2001).

12. For a good instance of technoscientists listening to a technology, see Orr (1996, 98).

13. Thanks to Arne Hessenbruch for conversations on this topic.

14. See, for instance, Sagan (1985, 43-44), where the heroine listens to the output of a radio telescope: "She heard, as always, a kind of static, a continuous echoing random noise. Once, when listening to a part of the sky that included the star AC + 79 3888 in Cassiopeia, she felt she heard a kind of singing, fading tantalizingly in and out, lying just beyond her ability to convince herself that there was something really there." See 27 and 52-63 of Dennis (forthcoming) for other examples.

15. The rhetoric about rendering software is similar as well—it is described as aesthetically pleasing and publicly convincing, but scientists are wary about according it epistemic status.

16. My thanks to Heidi Voskuhl and Kevin Connelly for discussions on this topic.

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