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ABSTRACT

In contemporary laboratory workstations, automation promises a technological fix for producing more robust workflows. By insulating the experiment from tacit or embodied knowledge, it is expected to produce more reliable output. This apparent tension between trustworthy disembodied protocols and the unreliable human factor should not, however, be taken at face value. Instrument operators routinely face uncertainties and instrument opacity, and their concerns may be further aggravated when processes are automated. In some contexts, therefore, researchers cultivate such embodied practices precisely to assure themselves of the reliability of automated instruments and protocols. This qualitative study of research practice in a multi-disciplinary research group in physics and materials science shows that researchers complement instrument readings with 'somatic vigilance', a set of laboratory practices that emphasize hands-on instrument knowledge, material witnessing and rely on sensory experience to monitor experimental processes. Equating physical and epistemic proximity to an instrument, operators use these techniques to monitor their instruments and to manage their own expectations. Operators' reliance on auditory information and sonic skills to monitor their instruments and their environment illustrates the value of somatic vigilance on the laboratory's work-floor. Connecting scholarship in science and technology studies on trust management and embodied practice, somatic vigilance calls attention to the continuous maintenance of both instruments and user expectations as well as the situated and often embodied techniques that are required to manage trust in instruments. More than an unreliable human factor, it suggests that researchers instead, conversely, consider embodied knowledge a way to fix automation.

KEYWORDS
Trust; senses; body; experimental physics; vigilance

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1. Introduction

Over the past decades, computer technologies have increasingly been used in the laboratory to automate the workload. With computers now an integral part of the experimental apparatus in fields such as biomedicine and high-energy physics, laboratory workers rely on software to steer experimental protocols, enable remote process control and analyze experimental output. Automation has been introduced to boost productivity and scale up basic experimental processes to industrial standards, but it has also been hailed as a way to disengage the researcher from the experimental protocol (Chapman 2003; Olsen 2012).

When deployed for tasks that are considered too routine, fatiguing or precarious for the experimentalist to carry out, automation may save time and improve efficiency. But according to its proponents, it may also significantly improve the quality of research. Automation, they argue, helps to deal with what some have called a 'reproducibility crisis' – the sense that methods and data are recorded too imprecisely for others to enable straightforward reproduction of reported findings elsewhere (Check Hayden, 2014; Baker, 2016). In response to this alleged crisis, predefined automated protocols have been advocated as a way of producing more robust, repeatable and thus reliable workflows. Automation thus promises a technological fix for restoring output reliability and the scientific community's trust in reported results, by insulating the experimental protocol as much as possible from the human factor.

Such claims stage a tension between a disembodied protocol that is deemed trustworthy and the problematic factor of human inattention, variable skill or simple tacit knowledge. This tension should not, however, be taken at face value. Firstly, as investigators of Science and Technology Studies (STS) have long shown, local, tacit or otherwise embodied practices of sense-making that often escape comprehensive documentation may complicate the easy transfer and trust in experimental protocols (Polanyi 1966; Collins 1974). But exactly for that reason, they have also been identified as key ingredients of robust experimental systems – they are essential to make experiments work. Second, a related strand of work in this field suggests that trust in technology is not usually given or stable, but is actually in need of careful construction and maintenance (Gooday 2004; Bruyninckx 2017). In spite of 'mechanical objectivity' continuing to be a widely held value in science and engineering (Daston and Galison 2007), operators' trust in the usefulness and reliability of their instruments is often subject to much local variation (MacKenzie 2001; Turkle 2009; Wylie 2018). This is particularly so in contexts of highly-skilled technical labor, such as scientific experimentation.

In view of automation's standing as a technological fix for enhancing instrument reliability and trust, and combining these two strands of scholarship, in this paper I ask how laboratory scientists actually engage with automated instruments on the work-floor, and how they manage their reliance on and trust in these systems? What role, specifically, do they allow for embodied skill? And how does such skill modulate relations of trust in the laboratory, particularly pertaining to relations of technological dependence, between researchers and their instruments as well as between their collaborators? I address these questions through a qualitative study of a multi-disciplinary research group that I will call 'PlasmaLab'. This laboratory operates in the fields of applied physics and materials science, a technology-intensive experimental field in which researchers routinely rely on a mix of (semi-)automated experimental setups and highly-skilled labor to complete their experiments (Pettersson 2011).

I draw on material collected by two observers between 2011 and 2013, using semi-structured qualitative interviews, participant observation, and casual on-the-job conversation for generally three days a week.[1] We joined research and technical staff on the laboratory floor as they prepared experimental runs, responded to instrument problems, assembled, maintained or repaired setups, taught new users, or collected and analyzed data. We also sat in on seminars, office work and breaks as lab workers discussed their work and planning, and we studied documents such as instrument manuals, logbooks and teaching materials. Interview questions were based on a thematic analysis of field notes and enlisted interviewees' help to interpret concrete observations. They aimed to elicit recurring problems, skills and experiences brought to solve them, and ways of sharing these among staff.[2] Although we each received basic entry-level instruction, we did not engage in actual, hands-on experimental research practice ourselves.

Based on this research, I argue that when researchers regarded automated setups as uncontested elements of the laboratory landscape at PlasmaLab, this was at least due in part to a sensory and material engagement with those instruments. I call this engagement 'somatic vigilance' to denote a set of laboratory practices that emphasizes physical monitoring, practical understanding and craft knowledge as a mode of engagement with automated or otherwise epistemically opaque instruments. This approach to the maintenance of trust in instruments is exemplified by the ways in which operators draw specifically on their auditory sense and 'sonic skills' – including listening skills and related technical skills (Supper and Bijsterveld, 2015) – in relation to the laboratory's material environment. These observations demonstrate that, more than a quality of the instrument or automation itself, trust in the instrument is continuously reaffirmed in an embodied relation with the operator.

The following sections first place this study in relation to existing scholarship in STS on trust management in the context of scientific research, to consider how automation, proximity and familiarity modulate feelings of trust. Section three develops the concept of 'somatic vigilance' with reference to scholarship on the importance of bodily and sensory practices in technical and scientific work. This concept helps to account for the problem of trust-management in relation to automated instrumentation. The following sections describe PlasmaLab researchers' concerns with their instruments and show how strategies of material witnessing and monitory listening play out in practice. A final section shows how practices of somatic vigilance not only modulate trust in the instrument, but also lead researchers to blur the division of labor between themselves and the technician.

2. Analytical Perspectives

2.1. Managing Trust, Between People and Instruments

In recent decades, social studies of science have extended a wide-spread concern with trust in the social sciences and humanities to the problem of epistemic authority. They have shown that trust and credibility play crucial roles in the constitution and maintenance of knowledge (production) systems (Shapin, 1994). Most knowledge claims, after all, cannot be practically verified in person, but have to be taken on trust. This observation has given rise to a body of scholarship concerned with the ways in which trust dynamics and credibility are managed; from seventeenth-century experimentalists' reliance on gentlemanly codes and literary techniques such as 'virtual witnessing' (Shapin & Schaffer 1985), to studies of trust mechanisms in relation to replication of experimental results, multi-disciplinary collaboration or ethics regulation (Krige 2001; Shrum et al. 2001; Hedgecoe 2012).

This work has yielded a detailed insight into the taxonomies and strategies that scientific workers employ to manage trust. In (experimental) physics, in particular, direct contact and personal exchange have been shown to engender personal trust, which served to overcome distrust resulting from failure to replicate reported measurements (Collins 2001). Such interpersonal trust is not only based on formalized indicators of competence, but often complemented with reputation or indicators of expertise (Collins 1985; Traweek 1988; Knorr-Cetina 1999). Recognitions of skill and competence have, for instance, often mediated trust-relations between technicians and researchers (Wylie 2018). When social and professional distance prevent validation or personal trust, trust is shown to be managed in other ways. As Reyes-Galindo (2014) shows, members of different theoretical and experimental communities in physics may choose to accept claims on a principled belief in their peers, the institution vouching for it, or simply on blind faith.

Much less systematic attention has been devoted to the trust that researchers extend to automated instruments or other inanimate epistemic objects (cf. Knorr-Cetina 1999). Classic controversy studies hold that experimental setups gain trust and reputation within a community when they show themselves to be reliable, transparent or otherwise uncontentious in their operation (Gooding et al. 1989). Once properties and effects of an instrument are considered known and reliable, they become 'black-boxed' as unproblematic technical objects (Latour and Woolgar 1986; Rheinberger 1997).

But as these and other ethnomethodological studies of laboratory operations or safety-critical technological systems have also shown, the stability of such technical elements is itself dependent on a fragile order of the broader socio-technical networks that they are part of (Henke 1999; Winner 2004; Sormani 2014). Such stability, therefore, is dependent on continuous maintenance and repair. Even when instruments and techniques are regarded as finely tuned and widely trusted by peers, the fragility of this order makes that they may, on occasion, behave more *or less* reliably or predictably (Gooday 2004; Bruyninckx 2017).

Taking a cue from such work, this paper starts from the premise that if instruments manage to become and remain uncontested elements of the laboratory landscape, this is due to scientists' abilities to keep them working properly and assure themselves that they actually do. Together with the instruments' reliability, in other words, users' trust in them needs maintenance too. After all, as sociologist Donald MacKenzie (1998) has shown, it are exactly the recurring instabilities that may introduce deeper epistemic uncertainties or even distrust. Citing a function he terms a 'certainty trough' across various cases of automated instrument applications, MacKenzie finds that certainty and trust in a technology are typically lowest among those users who are *most* familiar with its operation. Users' suspicion of the technology, he argues, is rooted in their awareness of the many contingencies that riddle its design and operation, but generally remain hidden from more casual users.

But if the 'certainty trough' suggests that a general sense of instrument reliability improves when a technology's operation is black boxed, some sociological studies of scientific and other workplaces, on the other hand, show that concerns tend to be aggravated when automation renders an instrument's inner workings opaque.

MacKenzie (2001) has also shown that mathematicians were deeply divided over the kind of trust they extended to the algorithms that automated their work; some could trust computational instruments *only* after they had verified the underlying code. Sherry Turkle (2009) has documented a similar concern and approach among physics and architecture faculty and students at MIT, who initially feared abdicating direct and practical knowledge of their instruments to automated protocols. Likewise, in her study on the transition from traditional and craft-based to computer-mediated task environments, Shoshanna Zuboff (1988) argues that industry workers struggled with what they perceived as a sense of distance, disconnect and distrust in data output, resulting from the automation of formerly craft-based industrial processes.

Although these authors have observed resistance to automation dwindling more recently, these references suggest that trust in an instrument's reliability is not a given. They indicate that such 'instrument trust', much like interpersonal trust, is mediated by relations of proximity and familiarity. Close familiarity and detailed instrument knowledge may be a source of uncertainty about an instrument's reliability, but may simultaneously serve as a strategy for producing trust in its outcomes. The examples cited illustrate that automation is seen as introducing a degree of opacity – a term that collapses the instrument's material and epistemic qualities. In the following section, I will further conceptualize one strategy to establish trust in automated instruments through material and sensory practices that I term 'somatic vigilance'.

2.2. Somatic Vigilance

As the previous section has outlined, instrument operators continuously engage in so-called repair work to assure themselves of the reliability and continued trustworthiness of their instrumental setup. Classic scholarship in STS has, after all, shown that making such (otherwise trusted) techniques work, requires craft, skill and improvization, as well as various kinds of tacit, situated and embodied knowledge (Collins 1974).

One strand of work in this field has begun to highlight the continued relevance of embodied and sensory knowledge in dealing with complex machinery or instrumentation – even in settings where technical instruments have long been presumed to outperform and replace the human sensorium (Knorr-Cetina 1999). Such work typically serves to undermine the traditional view that science is a predominantly visual and cognitive practice (Burri et al. 2011), by attending to scientists' everyday and material practices rather than to their presentations or written reports.

For instance, a series of ethnographies of computer-aided professional practices such as surgery, space exploration or brain scanning show how visual interfaces, computer simulations or data models mediate researcher's relation with objects under study (Alac 2011; Vertesi 2011; Prentice 2013). But they also show that such interfaces themselves do not eliminate the need for an embodied user, as gestures, touch or bodily positioning continue to insinuate themselves into their craft. Specifically, it underscores the many instances in which sophisticated (and often automated) instrumentation *requires* rather than *replaces* embodied experience.

Natasha Myers (2015), for instance, has shown how crystallographers engaged in protein modeling on the digital screen, tend to rely heavily on their own somatic experience, using their bodies as a resource to envisage proteins' complex forms and movements and explain them to others. In the same vein, Cyrus Mody (2005) observes that some researchers convert their sophisticated microscopes' outputs into various auditory and haptic signals, as a way of monitoring instrument breakdowns and to provide for what they considered a richer and seemingly unmediated experience of the instrument. Others have shown such sonifications to be used to relate the researcher in different ways to phenomena ranging from cellular interiors to gravitational waves (Supper 2015).

Sound, in fact, has been shown to play a particularly significant role – in the laboratory, as well as in a variety of other scientific, technical and medical worksites (Bruyninckx 2017; Bijsterveld 2018). As Bijsterveld (2018) has argued, drawing on historical and ethnographic work, a surprising number of practitioners in these sites tend to rely on listening in their everyday practice, to gain specific knowledge about their instruments or the objects under study. Drawing on an extensive typology of listening modes across these sites, Supper and Bijsterveld (2015), show that instrument operators deploy their 'sonic skills' – an acute ability for listening along with a skillful handling of instruments to do so – for a variety of practically and epistemically important purposes: to *explore* new phenomena, to *diagnose* technical malfunctions, and, in keeping with Mody's observations, to *monitor* instrumental processes. Attending to such different purposes of listening as well as to the ways listeners shift between them, the authors (2015) propose, may help to better understand how non-visual senses actually contribute to processes of knowledge-making.

In light of the questions raised above, I will build on this typology to attend to its role in providing epistemic and practical assurance as an often-noted but rarely explained function in the knowledge-making process. Bijsterveld (2001) has observed, for instance, that machine noises acquired a reassuring quality in the context of industrial labor because they informed operators that instruments were *working* as expected (p. 77). Likewise, Alberts (2003) has shown how operators at the Philips Physical Laboratory amplified the sounds of pioneer computers to substitute for rattles they had learned to rely on when working with mechanical calculators.

In this paper, I propose to conceptualize such instances as part of a technique of trust management in the laboratory that I term 'somatic vigilance'. I use the term to denote a set of laboratory practices with which operators actively supplement instrument feedback with somatic and sensory knowledge, as a way of assuring themselves of its reliability. This, I will argue, offers the operator a way to balance the material and epistemic opacity that they may experience in their technologies. This enables them to confront the deeper epistemic uncertainties that they associate with instrumental opacity, before they escalate into distrust.

As a technique of trust management, finally, 'somatic vigilance' is especially relevant to recent scholarship in STS which has highlighted the epistemic politics ongoing in the laboratory. Such work has shown that knowledge making in advanced scientific laboratories typically relies on a clear division of labor between research and technical staff, each of which is ascribed its own field of expertise and jurisdiction (Lynch 1998). One of the key responsibilities of technicians, for instance, is to buffer scientists from empirical difficulties and instrumental idiosyncrasies (Shapin 1989; Barley and Bechky 1994). Such divisions of labor have been justified by scientists who attribute technicians and operators with ‘skilled hands’ and an innate ‘feel’ for the equipment (Doing 2009) Such epistemic politics are particularly strong, such even that a belief in technicians’ tacit skill (and thus the social order in the laboratory) has been shown to be maintained when alternatives in digital computing are available (Wylie 2018).

This work suggests that hands-on and embodied knowledge is often implicated in relations of trust in the laboratory – not just between operator and instrument, but also between researchers and technical staff. Just so, as a practice that insists on the physical proximity and hands-on knowledge of its user, somatic vigilance may thus modulate relations of trust between scientific and technical staff. In the next sections, I will first introduce the laboratory setting, before analyzing why researchers insist on having a ‘feel’ for their instrument.

3. Empirical Analysis

3.1. Calibration and Getting to Know the Instrument

At Plasmalab, researchers study the application of plasma physics to surface materials. One important experimental line seeks to optimize processes for building ultra-thin atomic layers with enhanced material properties. Researchers rely on a complex system of vacuum chambers and pumps to measure plasma reactions between materials and gases under highly controlled conditions. Critical parameters are controlled by software-operated protocols, which operators can monitor through a graphic interface. The reactions between plasma, gas and surface can be examined using in-site sensors and ex-situ measurement technologies, such as spectroscopy, laser diagnostics or atomic force microscopes.

Most of the daily experimental work is carried out by around thirty post-doctoral and junior PhD researchers, under supervision of five faculty members. Four technicians are responsible for designing and manufacturing laboratory equipment, maintenance and repair tasks, and for monitoring safety procedures – in the laboratory as well as on campus. In addition, several undergraduate students typically work in the laboratory on small-scale assigned projects.

Research activities within the group are spread over two large facilities. The group’s primary location is a large open hall nicknamed the ‘lab garden’, which houses several custom-built plasma reactors and includes a separate section for high-power laser experiments. The group acquired fame in its field for the home-built setups with which it pioneered this line of research, but in recent years these have been supplemented by several commercially manufactured systems. These new systems are housed in a clean room that is shared with other research groups on the campus.

A significant part of the daily work in these laboratories is dedicated to ordering the various elements in an optimal and stable system. Most time is therefore spent on (re-) designing, building, installing, calibrating, and testing an instrument setup, and adjusting the parameters and protocols that are critical to making it work. The researchers either inherit a setup from their predecessor or consult with technicians to construct a new one. In a first phase, the setup is adjusted to suit their individual project. In a subsequent phase of trial and calibration, researchers seek to establish a system that is reliable and stable. Eliminating critical problems through repeated cycles of measurement and adjustment takes time, from several days (for routine realignments) to several years (for new doctoral projects). In a final phase, which usually takes only a fraction of the time that is spent on calibration, a more focused set of measurements provide the actual data. This run is typically repeated later again to collect the final data that is reported in a scientific publication.

As Sormani (2014, pp. 45–48) has pointed out, establishing a stable system in experimental physics requires not just a calibration of the instrument, but also of the operator. Through self-instruction, tinkering and trial-and-error, the operator gets to know the setup and learns about its specifications and limitations. At PlasmaLab, much in keeping with the culture of practical knowledge in their field, researchers cultivated a hands-on, practical attitude towards their experiments and instrumental setups (Pettersson 2011). In interviews, they would often recall their time spent as junior scholars while working at other laboratories, building, fixing or maintaining instrument setups – usually without the luxury of technical support. The discovery of a form of technical self-sufficiency typically brought a sense of personal accomplishment, which they often presented as formative to their identities as experimental physicists.

Because researchers spend so much time establishing their instruments' stability, the desire (and difficulty) of getting to 'know' their experimental setup was a common motif for my respondents, regardless of their experience level. For them, knowing an instrument required not only being able to use it by following a fixed protocol. It also involved gaining a 'deeper' understanding of its principles, its behaviors, blemishes and needs. Several researchers described this process as acquiring a 'feel' for their system:

> You have a certain kind of background if you have done this for years, so you have some kind of feeling for specific plasma and you … well, you don't have to know all the details but if you switch on a plasma you need to have a feeling and then you know: this is going to behave like this and this is going to behave like that.
>
> (Interview scientific researcher 1)

Such knowledge and the ability to anticipate an instrument's behavior is an important source of trust in the instrument. One of my interviewees, for instance, reflected on a long process of learning to operate an abandoned home-built diagnostic instrument. His predecessor had left only a brief set of instructions and protocols. Learning to calibrate and use the instrument had been a painstaking experience over a period of months in what, with the right expertise, 'could have been a few days' (Interview post-doctoral researcher 2). But in learning 'the insides, how it worked and all that stuff', such that he 'could just go and fix it', the post-doctoral researcher had discovered 'a level of confidence' – not just in himself but also in the instrumental setup, whose peculiarities he had now mastered.

Similarly, when I asked an advanced PhD researcher whether he felt his plasma deposition setup worked reliably, he responded with some hesitation; 'yeah, the thing is, ehm, you need to get to know your system. It is not reliable for the first two days when it has been used by another [user]. So I need to know what to do to make it reliable' (Interview doctoral researcher 5). Instrument trust, in other words, is generated in a process of gradual attunement between the operator and an instrumental setup. But that relation can frequently be thrown off balance by unexpected instrument behavior.

3.2. Weird Signals and Touchy Systems

However elaborate and reassuring, calibration does not immunize the setup against technical failures or unanticipated problems. Such instances are especially problematic during later measurement phases, because they tend to call into question the stability of the conditions under which data have already been collected, in effect rendering the experimental outcomes vulnerable to doubt. In many cases, such problems manifested themselves as what an experienced post-doctoral researcher described to me as 'weird signals':

> Everything is controlled by software, and then the software controls some electronics and these electronics control all kinds of valves and, ehm, those control gases and those gases have all kinds of indicators and it's just also remembering what goes where and what happens when. And then stuff breaks down, stuff goes wrong and then you see a weird signal and then [the question arises] 'what causes this signal?'
>
> (Interview post-doctoral researcher 4)

'Weird signal' problems are a recurring issue for PlasmaLab researchers, and can genuinely disrupt experimental practices. Most recurring problems are eventually classified as human errors or reduced to technical defects such as an erroneous input value or a broken sensor. There remains, however, a fraction of frequently recurring problems that operators attribute to the 'temperamental' nature of their systems.

One experienced doctoral researcher, for instance, recalled his particularly complicated relation with one reactor for atomic layer deposition, which for some time would 'go crazy' and break down in unexplainable ways when *he* used it. This made him the butt of technicians' jokes, who suggested the reactor was 'responding' to him individually. Explaining his frustration, he confided to me that 'there are many other things that happen in the reactor which you never know. Sometimes you actually think that the reactor has a personality' (interview doctoral researcher 5). His anthropomorphizing of the setup underscores a concern with the system's unpredictability.

Such concerns are echoed in researchers' frequent laments about the difficulties they experienced in making their improvised solutions 'stick'. Although researchers share a body of informal tricks that have sometimes proved to be effective remedies for instrument problems, these are often hard to turn into sufficiently robust solutions when the nature of the problem is not usually well understood.

This became apparent to us on several occasions in the lab garden. While trying to replicate a dataset for a publication, for instance, advanced doctoral researcher 4 had noticed that the gas flow in his reactor was unstable. Although he was not really sure about its cause, the problem seemed finally resolved when he changed a cable. Suspecting a loss in its capacity, he continued his measurements. We encountered him again two weeks later, consulting with a technician: the cable trick had apparently lost its effect and the reactor had stopped working altogether. Unsure of the cause himself, the technician proposed that the only solution would be to take the setup apart again. Because this would require the doctoral researcher to recalibrate anew, it effectively rendered his work of the past two weeks useless (Field notes, 06/06/2013 and 19/06/2013).

Although such problems are not exclusively attributable to software glitches, some researchers did feel that software-automation in particular added to the opacity they experienced with their instrument, and to a sense of unease regarding its stability. Reflecting on his current system, one PhD researcher expressed his concerns as follows:

> So, it is kind of like the software is between me and the instrument, let's say. And this of course is another problem. Because if the software has a problem, then I can't get access to the machine by myself. Because it is so interconnected that I can't just say 'Okay, I'll get rid of the software and do it myself.'
>
> (Interview doctoral researcher 3)

This quote illustrates a concern with abdicating operating control to the software that we encountered regularly among these researchers. The doctoral researcher underlined his point by comparing the home-built but automated reactor setup he was currently working on at PlasmaLab to the home-built setups he had learned to use in a lab where he previously trained. In his view, the 'connection with the tool, with the instrument, has been lost a bit in this passage from the rough and not properly constructed system [to] this well-made system'. In the 'rough system' at his previous workplace, he felt,

> you *know* the machine, so you know how to touch it, you know how to deal with that, you are completely … you are the automatization [*sic*]. It is not the computer. *You*

> have to deal with everything and, [at PlasmaLab] of course there is part of that—it is not completely automatized—but you are less in contact with the tool.
>
> (Interview doctoral researcher 3)

This researcher frames automation as a factor that impedes a 'direct contact', which he describes as a practical, even tactile, hands-on knowledge of the instrument. Not all researchers at PlasmaLab expressed a concern about the lack of contact that software afforded them with an instrument in the same starkly sensuous terms. But many did observe that large parts of their systems had become black-boxed. This had forced them to focus on getting in – and outputs right, rather than attend to the instrument's internal complexity. Here, one of the experienced post-docs above, who derived confidence from painstaking self-instruction, relates his experience in working with a brand-new 'top-of-the-line spectrometer' for the first time:

> It was absolutely a black box, you couldn't open it, it was a really dedicated piece of equipment and you basically don't try to [be?] on top of it. You measure with it, with an optic fibre, and it gives you nice results. But internally it was a completely different spectrometer from the ones I used to have in the past. And those I could open and I could understand them. It is a different principle, let's say. … But it had very strange behavior, like you moved your calibration a little bit and the results changed a lot. And I was like 'Oh my god!, how can I trust this equipment, I don't understand it, I don't know how –
>
> (Interview post-doctoral researcher 2)

As this passage suggests, knowledge of an instrument is limited in all kinds of ways. It is impossible to acquire 'deep knowledge' of all the parts of one's system, and researchers invest a considerable amount of trust that instrument builders, sample manufacturers and colleagues will have the necessary knowledge of these parts. This post-doc eventually felt sufficiently reassured by an expert relation at the spectrometer's distributing firm, who was able to educate him in detail about its principles and operation.

But his story also reveals an unease that is caused by the inability to simply open up a system and inspect its inner workings. As suggested by MacKenzie's (1998) 'certainty trough', these users' familiarity with the instrument has raised awareness of their own lack of knowledge or the many instabilities that riddle its operation. At the same time, its black-boxing tends to aggravate researchers' concerns, exactly because it renders the instruments' inner workings opaque and reduces their opportunities to get to 'know' them.

Much like MacKenzie's (2001) mathematicians or Turkle's (2009) physics faculty cited above, then, the interviewee believes that the ability to look 'under the hood' provides an important basis for trust in the resulting data. Researchers' concern with the ability to open their instrument black boxes further illustrates how the reliability of an instrument is not simply given, but is actively de- and reconstructed, along with the instrument itself. In the next sections, I will analyze some of the strategies that PlasmaLab researchers used to do so.

3.3. Material Witnessing

One of the strategies that PlasmaLab researchers developed to mitigate such concerns is to carefully monitor instruments' activities. Automation has to a large extent eliminated the need to be present on-site and in front of a reactor during a deposition process. Many of the commercial setups, for instance, allow researchers to log on remotely and monitor the processes from behind their office desks; presence in the clean room is typically required only for changing samples and activating a new recipe. With deposition cycles often lasting up to a full day, the automation of monitoring tasks let researchers get on with other work tasks (such as data analysis) off-site.

But there were also researchers who insisted on being physically present around the setup when in operation, during calibration as much as when taking repeat measurements. Sometimes their insistence had a practical origin: since the laboratory complex is located in a different building, some felt that particularly for short deposition cycles of only half an hour, it was not worth their while to walk back the short distance to the office. But their practical motivations were also often presented in connection to the concerns described above.

When asked about the difference between on- and off-site monitoring techniques, one of the senior post-doctoral researchers in the laboratory motivated his own approach to remain on-site by saying that 'I am a bit more the old-fashioned guy, so I like the oscilloscope where you can see something on the screen and where you can really influence what is going on. Others like the automated systems where you just put in a file name and that's it.' (Interview scientific researcher 1). Contrasting both approaches, he distinguished between his active monitoring of processes *in time* and a more passive, post-hoc evaluation of data. Monitoring required a physical and attentive presence, as another doctoral researcher explained to me:

> I need to be in front of the reactor, I need to focus on what is happening and actually, I *want* to do that. Because you really learn how to notice things. Because you, more or less, always do the same process. So if you pay attention—and you *should* pay attention—when you see something different, you would notice it for sure. And if something is different, that means that something is wrong in that moment. This is something that you can do only if you are there, in front of the process.
>
> (Interview doctoral researcher 3)

As this quote indicates, individual researchers cultivate physical presence and active witnessing, firstly as a way of learning to understand a system's behavior and secondly as a way of monitoring the system's stability (and hence attest its reliability). These play into each other: it is only through learning to pay attention to the subtle cues emitted by an experimental setup that researchers can convince themselves to place trust in the tacit knowledge they have gradually come to accrue. In contrast with other strategies of credibility witnessing, this witnessing is material, and serves to convince the operator him- or herself rather than peers outside the lab (cf. Shapin and Schaffer 1985; Reyes-Galindo 2014).

Researchers' insistence on physical presence is a key component of somatic vigilance. Presence allows researchers to monitor instrument processes by relying not just on instrument displays, but also an array of sensory cues. Especially in the lab garden, we would frequently encounter researchers, seemingly idling next to their reactor while deposition was ongoing. They would pace around, chat with peers who were working on other setup stations, and read articles or answer emails on their laptops. But they were also attending in several ways to instrumental processes. Researchers would be monitoring the deposition cycles through visual or numerical readings on instrument displays or their laptops. But as I will explain in more detail below, the setup's sounds of rhythmically opening valves, gas release or activated pumps, also permitted auditory monitoring of its operations. Moreover, every ten minutes or so, they would pace around the reactor: touching the metal piping with their hands, they checked the presence of heat or vibrations, and squinting through the reactor's small porthole, they checked for unexpected gas flow movements or the shading of plasma. This, they explained, allowed them to gauge whether the deposition cycles unfolded as expected.

On one occasion, for instance, our informant became concerned about a pink hue that was deeper than he had witnessed during previous calibration and experimental runs. He suspected that the color was caused by a reaction with a residual element – which he assumed could only be produced by material particles left on the reactor walls or in a precursor gas that had not yet been purged completely. This observation made him visibly nervous. Concerned that this would affect the consistency of his data, he interrupted his data collection campaign to identify the culprit. When we asked him about the pink hue in an interview later, the doctoral researcher conceded:

> Sometimes I overreact about something that happened but that does not influence necessarily your system in such a way as to give you a problem. Eh, but you notice things and, the first instinct is to trust more what you feel than what the system is telling you. And so, I always double check or I always do it again, because of this reason. [Because] it is {pause} a machine, I trust more my own, my own thoughts, my own perception of the instrument. Actually, this should not be the case, because instruments are way more sensitive than you are.
>
> (Interview doctoral researcher 3)

As this quote suggests, for those who incorporate material witnessing in their laboratory routine, sensory information provides an additional interface that can be compared with the information that the system itself provides. At no point did sensory information actually *replace* the visual and numerical readings and output that researchers eagerly collected from the system displays. Rather, they served as a complement, helping to triangulate feedback.

At the same time, as the interviewee indicates, these sources are also weighted differently: while he concedes that sensory cues such as color or heat are not necessarily more *reliable* than his instrument readings, he does tend to regard them as more *trustworthy* indicators. The quote also highlights the operator's personal sense of ambiguity about this preference. Further in our interview, he described this kind of trust as 'subjective' and even 'irrational'. This was not just because his reliance on physical presence to attend to an instrument and make manual adjustments is more labor-intensive and often inefficient. It was also because he reflexively identified this insistence on material witnessing as a response to previous experiences with unstable or problematic instruments.

As such, this quote highlights how material witnessing serves as a strategy for managing instrument trust; its empiricism not only serves to monitor instrument behavior and locate possible issues early on, but also to manage the operator's own experiences and expectations regarding such instrument behavior. Close familiarity and detailed instrument knowledge, in other words, may not only introduce uncertainties about an instrument's reliability, but, in reducing proximity to the instrument, physically and epistemically, they also serve to reassure the operator that instruments work as expected.

3.4. Reassuring Sounds

One of the most common expressions of somatic vigilance that we identified in PlasmaLab was researchers' monitoring of the sounds that instrumental setups emitted. Especially around the home-built setups in the lab garden, experienced operators attended to the clicking sounds of valves opening and closing, the whooshes of vapor precursors mixing, or turbo pumps turning on and off, accompanying the process of atomic layer deposition against the noisy laboratory soundscape.[3] One informant, an advanced graduate student, explained his reliance on the attentive ear as follows, echoing the concerns outlined above,

> the setup is automated so that it can be operated fully via the desktop monitor, but I always listen. You know that when you enter this [value], you should hear this sound … . I don't trust the button {pause} you know, it is just a machine, something can go wrong. When I hear it, I know it for certain.
>
> (Field notes, 11 July 2013)

As the quote above suggests, listening serves as a way of detecting technical failures even before the software does, and researchers and technicians routinely draw upon them to diagnose technical malfunctions or 'weird signal' problems. On several occasions, we witnessed vocal impressions ('It just does bwwwww') being used in informal hall-way talk as junior researchers consulted their senior colleagues or technicians to determine the source of an instrument problem that had become evident from the data readings. On those occasions, at least, vocal impressions did not immediately resolve the issue. Although these episodes illustrate operators' common awareness of sound as a potentially useful indicator, they also demonstrate how much sound is an element of tacit embodied knowledge, and therefore difficult to trigger in someone else (Mody, 2005).

Because calibration of one's aural sense takes time, operators used it to different degrees and with varying success. One doctoral researcher, for instance, explained to us that in her previous laboratory, a specialized technician had been in charge of a particular setup. Upon her transfer to PlasmaLab, he had advised her to listen carefully to the pressure pump, to determine the pressure point at which it would be safe to proceed with her protocol. But for several weeks after her arrival, she still did not feel confident trusting her sensory intuitions over the instrument reading: 'If you trust the pressure sensor, that is more accurate than just listening to the, "okay, now it's right". Well yeah, I am not a musician, I don't like this {laughs}' (interview doctoral researcher 6). As her tongue-in-cheek remark reminds us, the ability to use auditory cues for knowledge acquisition is a learned 'sonic skill' that requires both technique and practice (Bijsterveld 2018). For lab workers, much as for a musician, such skill requires both an ability to use one's ears and a technical ability to handle the instruments. Without such learned ability, to the novice user, aural cues mean nothing.

What, then, makes such sonic skills particularly useful to PlasmaLab researchers in monitoring their instruments? As Alexandra Supper and Karin Bijsterveld (2015) have argued, listening is not one single practice, but may be conceptualized as different modalities, based on the different *purposes* (such as monitory or diagnostic listening) and different *ways* of listening (such as analytic or synthetic listening) for and with which they are employed. Listeners, they show, often deliberately shift between different modes to underpin their knowledge claims. At PlasmaLab, likewise, researchers and technicians typically alternated between synthetic and analytical modes of monitory listening. It is this 'multifocal' orientation – attending to subtle changes in the soundscape while being able to focus closely on acute instances – that makes listening a frequently employed tactic of vigilance in researchers' monitoring practice.

Monitory listening yields an awareness of the total material surroundings in the laboratory, supplying a kind of auditory counterpart to the visual concept of order and traceability that often underlies the safety culture of a large physics laboratory. Irregularities in the laboratory's soundscape alert researchers to possible disruptions: malfunctions at nearby setups or possible hazards (such as gas alarms or people entering the laboratory during laser experiments). As one post-doc working with high-powered lasers intimated, listening helped him not just to monitor the functioning of his own instrument setup, but also to keep an ear on other experiments ongoing in the laboratory, and ensure his own safety amid the active equipment. When laser experiments are under way,

> you enter the lab and you immediately know 'that [the sound of the laser] is not 10 hertz'. Because you are so used to that [sound] and so you hear changes. Sometimes this laser can become too strong or the focus too intense, or you're not doing the right thing. It can really ignite, you know, cause a mini-explosion, because it is focusing so much energy in one point, you know. You definitely hear that, it is very strong. Those are important clues.
>
> (Interview post-doctoral researcher 2)

Supper and Bijsterveld's (2015) typology of listening modes may help here to explain why listening, in particular, is a preferred strategy of somatic vigilance. Listening provides a way to extend one's physical presence in several directions possible. When listening *synthetically*, operators may monitor instrument processes in their surroundings while doing other work. However, the operator may also switch to listen *analytically* and try to individuate specific sound sources upon closer inspection. Operators would, for instance, alternately attend to the entire laboratory soundscape and single out specific sounds, such as the closing of valves inside the chamber or the rotation frequency of a turbo pump – at a nearly inaudible 80,000 rotations per minute, they would use a screwdriver against the machine to listen for its buzz. Listening may thus trigger different relations with the instrument.

Although listening was just one of multiple sensory and embodied tactics of material witnessing at PlasmaLab, these multiple functions illustrate how somatic vigilance helps operators to maintain some form of trust in their instruments, even in spite of routine instabilities or their black-boxing by processes of automation. Monitory listening can situate the listener in a shared auditory space of the laboratory. This allows, on the one hand, researchers to attend to the laboratory's social and material environment. It is in this way that operators claim to discover irregularities quicker, or in ways that otherwise go unreported by the system. On the other hand, listening serves to penetrate the physical casing that turns an instrumental system (literally) into a black box. Just as scientists elsewhere use sensory techniques (such as sonification) to interpret and situate themselves in alternative ways to the phenomena under study (Supper 2015), so too do PlasmaLab researchers rely on embodied skill and sensory awareness to situate themselves in closer relation (or even *inside*) their instrumental setup.

3.5. Technical Independence

As the sections above demonstrate, somatic vigilance serves some operators as a strategy for maintaining insight, and therefore trust, in their often automated instruments. But by emphasizing physical proximity and hands-on experience with the instrument, practices of somatic vigilance also tend to modulate relations of trust between scientific and technical staff. This becomes particularly evident in the ambiguous relation that the researchers in the laboratory garden maintain with the technical staff. In some fields, technicians are seen as a source of low-grade, highly routinized labor (Shapin, 1989; Lynch, 1998). Although at PlasmaLab, technicians are regarded as an important and reliable source of knowledge and skills that researchers often do not possess themselves, scientists at the same time, were also keen to avoid a relation of dependence with the technical staff.

In interviews and informal discussions, PlasmaLab researchers often described the technicians as having a privileged understanding of black-boxed instruments and their inner mechanics. Having worked with these instruments for years, they were seen as not only possessing some specialist knowledge of specific applications (such as laser optics or vacuum setups) but also an instrumental memory, a record of their extensive histories of alteration, their blemishes and wants. But although these researchers do rely extensively on technicians' aid for particular tasks, they also identified theirs as a particular expertise. Researchers never explicitly challenged technicians' expertise, but in interviews and in their daily practice they did subtly differentiate it from their own. They did this, for instance, by identifying gaps in technicians' knowledge (due to their technical specialization) and by insisting on the need to acquire instrument knowledge of their own.

> 'They [technicians] know how some equipment works, and they know how to build stuff and how to do other types of stuff. But they don't necessarily understand the experiment. They maybe do not necessarily understand the physics of the experiment, so they may know how this piece of equipment works, but you may be using this part and that other part to do something … they don't know the whole thing, they don't know what you need, so that's up to you, to get the information they can, the help they can give you. They can implement it in what you need. But again, a postdoc like me tries to be more independent. If you can do things yourself, you do' (interview post-doctoral researcher 2).

Particularly in the lab garden, researchers strove to avoid dependence on technicians' instrumental knowledge and abilities whenever possible. Researchers admitted reluctance to call upon technical support before exhausting all the possible diagnostics and tricks known to them or their peers. Their motivations were at once practical, social and epistemic.

In a laboratory housing over thirty active researchers, the technicians were under constant time pressure; amid planned maintenance sessions, safety responsibilities on campus or instrument design, they could not always make themselves available for immediate or extensive troubleshooting. For that reason, an overt dependence on technicians' support was also discouraged by the technicians themselves. The technicians' teasing of a doctoral researcher who failed to keep a specific instrumental setup running without technical interruptions may be read in this way. What to the researcher had appeared like a particularly temperamental instrument, to the technicians had reflected upon his operator skill and thus standing within the laboratory – even if they too often struggled to troubleshoot his issues.

But reversely too, researchers' reluctance to involve technicians too quickly was also related to their concern that too strong a dependence on technicians' know-how could affect their own knowledge of the instrument. Even where technical support might be on hand, researchers were aware of the benefits they would reap from developing and fostering their own technical capabilities and a working knowledge of the setup, for future occasions. One researcher explained his hesitation to invoke technicians for help as follows:

> I really want to know what is going on in the setup and maybe I can also even fix something myself without calling them [technicians]. And it's also much better if you want to understand your results, because sometimes you have really technical or engineering [issues] on the question of why your results are so strange [when] you expect something very different from your scientific point of view.
>
> (Interview scientific researcher 1)

This voices a concern among researchers that technical dependence might perpetuate instrument opacity rather than eliminate it. In response, researchers often resorted to troubleshooting with help of their peers or tried to extract as much knowledge as possible by actively observing technicians' repair runs. Technicians, in other words, were both a source of potentially valuable knowledge of the information and a possible source of opacity and obstruction to obtain more intimate knowledge of the instrument.

This is at least remarkable. During their fieldwork in molecular biology, Barley and Bechky (1994) observed that one of the technician's key responsibilities was to buffer scientists from empirical difficulties and instrumental idiosyncrasies, while scientists designed and conducted the experiments. As Doing (2009) has shown, this division of epistemic labor would typically be legitimated by means of identity work; scientists portrayed technicians as having an 'innate' ability and intuitive feel for equipment, so-called 'lab hands', rather than the experience technicians themselves claimed to have learned. Such clear divisions of epistemic labor may frustrate technicians, who often remained skeptical of scientists' actual instrument knowledge. But as Wylie (2018) shows, they may also result in each party trusting each other's expertise, effectively stabilizing the social order in the laboratory. In the paleontology lab that she studied, for instance, scientists and technicians jointly resisted new digital imaging technologies for fear they would threaten technicians' skill-based practice and affect the laboratory's social structure.

Such work alerts us to the ways in which embodied skills may be implicated in trust relations in the laboratory. But it also highlights subtle differences in scientists' epistemic politics at PlasmaLab. On the one hand, a similar kind of identity politics could be observed, with scientists explicitly acknowledging technicians' privileged instrument knowledge and memory. On the other hand, scientists invested in seeking opportunities of their own for acquiring the deep instrument knowledge and a 'feel' for the instrument that they deemed necessary. Seeing this kind of knowledge less as an innate ability than a product of experience, researchers attempted to absorb technicians' knowledge and skill where possible. In doing so, researchers simultaneously affirmed and blurred the formal division of epistemic labor between technicians and themselves.

4. Conclusion

In this article, I have investigated how laboratory scientists manage trust in automated instruments and what role they allow for embodied skill. My qualitative study at PlasmaLab shows that researchers actively cultivate an embodied interaction with their instruments. The concept of 'somatic vigilance' allows us to interpret researchers' diverse and individualized practices as techniques for assuring themselves of the reliability of the black-boxed instruments and automated protocols that populate the laboratory. This analysis suggests that embodied experience does not just complicate but actually also contributes to the perceived reliability of experimental outcomes. This finding suggests that automation can only produce robust outcomes by taking trust's multidimensional nature into account.

(Semi-)automated systems may inspire trust in the reliability of their output among outsiders, but among these researchers, they also raised concerns over their epistemic opacity. Cast as an additional layer that sits 'in between' the experimentalist and the setup, automation contributed to a sense of distance and disconnect in relation to the experimental system. Such distance was experienced both physically and epistemically, through the instrument's material black-boxing, its automated control at a distance, or researchers' dependency on technical staff to understand its internal workings. These operators' main concern was not that automated setups are more prone to technical failure, but rather that when deviations inevitably occur, automation might allow them to go unnoticed or to make their source difficult to locate; sensors may fail, slight fluctuations might not register, or instrument readouts may not provide vital clues.

Such concerns can be found across scientific disciplines, but they may be particularly prominent in experimental physics. After all, its causal epistemology and a focus on a world of phenomena separate from the investigator's environment, makes learning and stabilizing the apparatus of crucial concern to the researcher (Knorr-Cetina 1999).

At PlasmaLab, researchers responded to these concerns by trying to reduce technical dependence, insisting instead on first-hand knowledge. They cultivated an ability to take instruments apart, to look (often literally) under the hood, or monitor their processes through direct sensory and somatic feedback. Together, these practices did not substitute their reliance on automated setups or protocols with sensory feedback altogether. Rather, these techniques aimed to establish the knowability and predictability of their systems by triangulating different forms of instrument feedback.

This helps explain why these researchers challenged the traditional division of labor within the laboratory, in which technicians are typically ascribed responsibility for instrumental instabilities as well as particular skills for handling those. Although labor-intensive, researchers often sought to keep charge over monitoring and diagnostic tasks as much as possible, because it provided them with a sense of confidence in their own abilities as experimentalists and in the reliability of their system.

Somatic vigilance thus calls attention to trust as a practical, individual and multi-dimensional process. As existing scholarship on trust and credibility in knowledge production has shown, trust management often involves ways of bridging physical, social and epistemic distances. Trust is therefore often founded on principled beliefs, trusted proxies or community-valued techniques such as extensive description of experimental procedures (Reyes-Galindo 2014; Shapin 1984). But just as interpersonal trust is often founded on the assurance of personal acquaintance, so too do researchers tend to trust instruments when they can verify their internal operations 'in the flesh'. Further, trust is not only individually attested, but also continually affirmed. More than zero-sum states, instruments' reliability *and* researchers' trust in them are both subject to ongoing maintenance (Henke 1999).

Finally, somatic vigilance reminds us that trust itself tends to refract in a multitude of trust vectors. Researchers may seek trust in their collaborators and peers, but within the laboratory, they may also experience trust in technical staff or their instruments. Those relations are related but not the same. Automating experimental processes may, in other words, promise a technological fix for restoring the scientific community's trust in reported results. But as this article has shown, insulating the experimental protocol as much as possible from the human factor may interfere with existing trust management techniques in the laboratory.

Notes

1. I would like to thank Aline Reichow for collecting part of the qualitative data cited here and for permitting its use in this paper.

2. Individuals, institutions and places have been pseudonymized for this article.
3. For an impression of a typical soundscape in a materials science laboratory, see Karel (2010). *Heard Laboratories* (CD). And/OAR 35. Particularly track 1.

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