

Interpreting Graphs as Emergent Competence:

A Cultural-Historical Approach

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ABSTRACTH: We report on a new study conducted in a biology laboratory where the investigators conduct microphotospectrometry of fish retina. Because of the cutting-edge nature of the research, it is often not clear what a particular graph means, which aspects are meaningful signal, and which aspects constitute noise or artifact. By coming to understand the emergence of graph readings in this complex situation, we illuminate the discussion of graphs and graphing competencies where social science researchers' presuppositions cloud the pertinent epistemological issues.

Research on graphing ordinarily asked participants to make inferences about the meaning of graphs without ascertaining that these participants are actually familiar with the conventional *rules* established by the (scientific) *community* or with the phenomena that said to be represented in the graph. Recent research showed that in such situations, not only students but also experienced scientists have difficulties reading graphs when they are not familiar with conventions or the phenomena (Roth & Bowen, 2001a; Roth, Bowen, & Masciotra, in press). On the other hand, when individuals are explaining graphs that have arisen from their own or similar work, they are highly competent. The

present study further illuminates the emergence of competent graph use and graph interpretation and shows how scientists in activity appropriate (internalize), in some situations and under certain circumstances, previously-external tools of graphical analysis. As a result, scientists' reading of graphs is intimately tied to an understanding of the phenomena and instruments involved in the data collection. Our research provides evidence that competent reading of graphs is the result of a historical process in which previous results (and understanding) become internalized (in subject or tool [e.g., computer]). At any one point in time, competent graph reading is based on built-in prior results of human activity. In this paper, we provide evidence for these aspects of reading graphs and the process of internalization. The following excerpt raises the central problematic addressed in this paper and exemplifies our approach and results.

In cutting-edge scientific work, the nature of a graph is often ambiguous. Its exact nature (as fact or artifact) is yet-to-be determined. MR, being new to the laboratory, asked whether the graph displayed on the monitor was a sign that an UV cone had been in the collimator.

MR: Is this a UV cone?

TH: I think there is a potential hump here [*on right shoulder*] and a little hump there [*next to major peak*] but it is very hard to read.

CH: °You need the spectrum°, to put on...

TH: You want to rescan it?

CH: No, go on to another cell. There is too much in here that I don't want to look at.

TH: OK



Rather than making a definite interpretation, the research associate TH suggested that there are peaks (“humps”) potentially of interest. The senior researcher CH, who also prepared the specimen in the microphotospectrometer, suggested that another spectrum

not presently available on the monitor “had to be put on,” presumably to facilitate the interpretation. TH proposed to rescan the cell, but CH decided to go on and to try another specimen—the searched-for signal was *probably* not there.

Here, the two scientists collaboratively achieved the reading of the graph. This reading was not based on pure inference but was mediated by the graphs displayed in the following ethnographic field note (Figure 1).



The shape of the curve in the UV region [left]. The high values are legitimate given that the photoproducts resulting from chemical changes in the retina are expected there. There is also a absorption effect. Only the right part of the spectrum is really of interest [bottom], and it is this part that is plotted in the curves on the board in front of the lab. There is an increased amount of UV absorption due to bleaching (see middle graph). This absorption is legitimate, both because of the photoproducts and because of the spectrum.

Figure 1. Graphs and conceptual underpinning that mediate the graph-reading episode.

Accordingly, chemical changes in the retina produce substances that absorb light in the UV part of the spectrum, thereby cluttering any expected peak from a UV-absorbing cone. Although not made explicit, the graph reading in the above episode embodies the scientists’ understanding and prior experience with the graphs on the right. Because of their extensive experience, they do not make the graphs on the right explicit. However, in other situations that we present in the paper, graphs are actually made visible on the computer monitor so that a direct comparison between a previous and the to-be-

interpreted graph is made possible. Of course, the relationship of the scientists to the graph, the *object* of their inquiry, was also mediated by the scientific community, which expects them to produce clear signals and “unambiguous” evidence for the phenomenon of interest.

What is to be taken as a salient aspect of a graph is not known a priori that is, without knowledge of the natural system. All evidence shows that graphs, graph-producing tools, and familiarity with the phenomenon mutually constitute and stabilize each other. This became quite clear when MR first joined the biological laboratory. Despite his physics and statistics background and despite years of research on the topic of graphing, MR could not correctly interpret the graphs that were the result of a data run. That is, interpretation could not be based on a purely inductive process. Even the nature of the relevant graphical feature was not evident so that during the early part of our research, MR was frequently attuned to features not at all salient to the resident scientists. The difficulties faced by a novice reader of the graphs become apparent from the four examples in Figure 2 and the collectively achieved interpretations.

In the first two graphs of Figure 2, analysts might be tempted to identify two features each that appear at about the same locations in the wavelength spectrum. However, the analysis of the laboratory interactions between the two scientists who collected and online interpreted these graphs, left little doubt that the left (Figure 2a) pertained to a blue retinal cone whereas the right (Figure 2b) pertained to a red retinal cone. That is, in the first graph what was salient to the scientists is the first, smaller peak whereas in the second, the right (smaller) peak predominated in their perception and interpretation. Yet, a quick inspection of the two graphs shows that the left peaks in both are almost identical.

How then do the scientist come to look at the right graph and apparently looking through its left peak without paying any attention to it as if it was transparent or even invisible to the eye? One might ask, how do scientists come to the point of articulating the left hump in the first graph and the right hump in the second graph as the signal and the other hump as noise, respectively? When scientists began researching a particular phenomenon they did not and could not know what the “right” peaks are, that is, how to “correctly” interpret the graphs that they have at hand. And yet, after some time they developed a competence that allowed them to make assessments, among others, increasingly quickly and without hesitation.

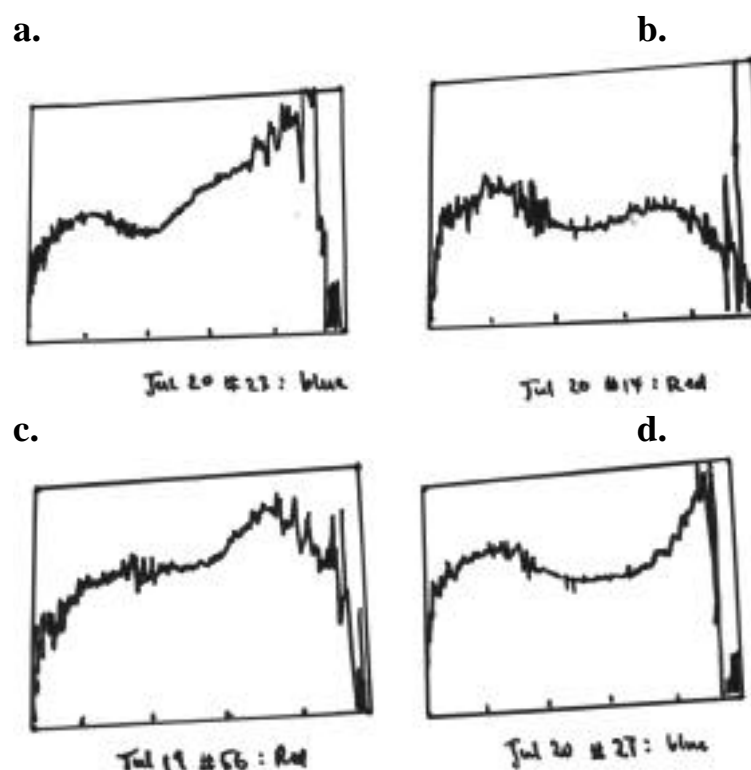


Figure 2. Four graphs as they were produced online during experiments in a biology laboratory. Whereas the scientists familiar with the apparatus and the biological system at hand make clear identifications, a person unfamiliar with biology and physics of instrumentation does not know what to interpret and how to interpret it.

These decisions are all the more remarkable given that a third curve (Figure 2c) was regarded as consisting entirely of noise and not referring to a cell at all. Here, the potentially misleading second peak in the blue part of the spectrum (left) has disappeared and the peak in the red part of the spectrum predominates. It is also much more pronounced than the red peak in the comparison situation. In the fourth situation (Figure 2d), CH and TH decided to discard the graph because it was “too wide.” If this blue part of the spectrum is overlaid with the other blue spectrum, one recognizes that they are virtually identical. Yet the scientists retained one but not the other of the graphs as data for further analysis. What mediated the situation was the fact that the final analysis (and therefore retention for publication) would ultimately be made in a subsequent analyses. TH largely conducted these analyses using a variety of graphical analysis tools such as detrending, pixel-shifting, curve fitting, smoothing (Fourier transformation).

PROBLEM

Research on graph interpretations generally assumed that sufficiently intelligent individuals should be able to interpret graphs even if these are unknown to them; that is, this individuals should be able to make inferences about natural phenomena given a graph. Implicit in this approach is the assumption of an underlying isomorphism between mathematical structure and the world. Students are often asked to interpret unfamiliar graphs and make inferences about the natural world (see review by Leinhardt, Zaslavsky, & Stein, 1990). However, this assumption is inconsistent with many recent findings in the social sciences. First, graphs, as all signs, bear an arbitrary relation to the thing that they express (Eco, 1984; Latour, 1999). Knowledge of the cultural conventions underlying sign use is required. Second, graphs are sufficiently complex that the particular aspect

that expresses something about the world is not clear; that is, just which aspect of the graph signifies a relevant phenomenon is inherently underdetermined (Roth & Bowen, 2001a). Third, the assumption of an isomorphism between graphs and some phenomenon does not allow us to appreciate the difficulties underlying interpretive processes. In order to get a better understanding of graph interpretation, we investigated sufficiently complex situations where the nature of the graphs, corresponding natural objects, and the relation between the two are not yet known and therefore the interpretation is highly uncertain.

In this article, we analyze and theorize knowing and learning related to graphs in a scientific laboratory doing cutting-edge research. This research allows us to document and theorize the work that actually goes into the construction of the natural object, graph, and the relation between the two. In the process of doing their research, scientists learn to see natural objects in their graphs, and forget about the constructive work that set them into relation in the first place. As a result, graphs, natural objects, and the relations between the two are the outcomes of historical processes of scientific activity systems. It is by amnesia of these constructive origins that graphs and natural objects come to be seen as isomorphic.

Our research distinguishes itself from traditional research on expertise in that we are interested to understand the processes of knowing and learning when scientists (experts) work at the very edge of their own understanding. That is, our research is concerned with knowing and learning in situations of uncertainty rather than in situations where the solutions to “problems” are highly standardized and over-learned and have achieved paradigmatic status. In this way, we achieve a better understanding about the difficulties inexperienced students face when asked to interpret unfamiliar graphs.

ACTIVITY THEORY

We theorize graphing in terms of the cultural-historical approach embodied in activity theory (e.g., Engeström, 1999; Leont'ev, 1978; Vygotsky, 1978). Activity theory explicitly recognizes that human activity is never based on *immediate* subject-object relations (e.g., individual-graph) but that such relations are mediated. In this, activity theory includes subjects, objects, tools, community, rules, and division of labor. These entities and the multiple mediated relations (all possible triangular constellations) are embodied in Figure 3. For example, the relationship between the collaborating scientists (*subject*) and a graph (*object*) is mediated by the *tools* that they have at their hand in the laboratory. These tools include scientific discourse, graphing software, apparatus, and so forth. Simultaneously, the relationship between *subject* and *tool* is mediated by the historically evolved (scientific) *community*, which characterizes and is characterized by the specific legitimate practices that are associated with each tool. The *community*, for whose “consumption” the graphs are produced, also mediates the relationship between scientists (*subject*) and the graph (*object*). That is, the overall activity, the production of knowledge (itself embodied in some graph) motivates the activities of both the individual research group and the research community. Because of the mediational nature of human activity, particular readings/interpretations are contingent on the community, its tools, rules, and division of labor. Even though a graph might look the same to an external observer, it will acquire different meanings in different social contexts because of differences in the community-mediated motivation for an activity, available tools, particular graphing conventions and so forth.

In activity theory, each entity has its history and unfolds in time. For example, the tools used undergo changes in order to address problems that arise in the course of research and these changes have their impact on the activity. As another example, in the course of their inquiry, scientists increasingly make assessments about graphs without requiring assistance from the graphical software. That is, the scientists change resulting in observable and analyzable changes in individual actions and in the overall activity system. Activity theory is therefore an analytic tool that allows us to situate graphing in multiple mediated and mediating contexts and as the product of a cultural-historical development. Two recent studies showed that activity theory is an ideal tool to theorize graphing at work and during the transition from school to everyday settings (Roth, in press; Williams, Wake, & Boreham, 2000).

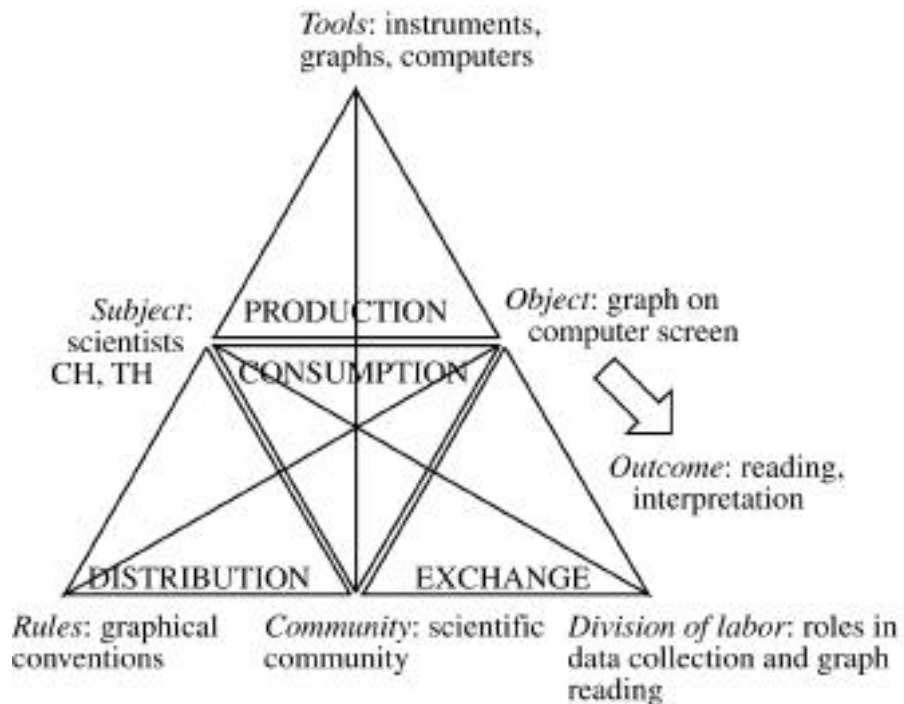


Figure 3. Activity theory conceives of human activity in terms of mediated relations.

Activity theory distinguishes activity from actions and operations (Leont'ev, 1978). Whereas an activity is characterized by a collective (community-mediated) object/motive, actions are oriented towards specific goals and therefore constitute individually defined aspects of the overall activity. Below collective activity and individual actions lies the level of automatic operations that no longer require conscious attention to be accomplished. In the academic community, constructing new knowledge is a principal activity. One goal in the construction of a research article is the writing of the theory section, which therefore constitutes an action. For many academics, the keyboard (pen) has become transparent to the process of writing the theory section; typing (writing) has become an operation and no longer requires attention.

From the perspective of activity theory, knowledge is not so much a collection of real entities that, in learning, are internalized; rather, knowing and learning are thought in terms of “engagement in changing processes of human activity” (Lave, 1993, p. 12). This engagement is to be understood in its historical and historically changing context. Furthermore, context itself is not understood as something an individual is put into and in or towards which an individual acts, but as an order of behavior of which the individual is part (McDermott, 1993). That is, knowing and learning graphs are historical processes; to understand these processes, we need to study the “choreography” of the situation that produce moments of their public appearance.

PRIOR RESEARCH ON GRAPHS AND GRAPHING

Research on graphing has by and large focused on psychological dimensions of knowing, use of, and learning about graphs (e.g., Leinhardt, Zaslavsky, & Stein, 1990). It therefore comes as little surprise when this research has focused on “deficits” of students

and novices with respect to graph-related activity, including graph production and interpretation. Researchers variously characterize students in terms of lacking “the mental tools to engage in a high level construction or interpretation of graphs” (Berg & Smith, 1994, p. 549), misconceptions (e.g., Clement, 1989), or “knowledge in pieces” (Moschkovich, 1998). Whereas such approaches definitely have had some explanatory power, they obviously failed to account for the mediational role of tools, community, rules, and division of labor. Consequently, these approaches did not account for the fact that highly trained and experienced ecologists made errors in interpreting graph that were very similar to those made by students (Roth & Bowen, 2001a). The psychological (deficit) approaches failed to account for the consensual nature of mathematics, which “is expressed and described mathematically; that is, it is available in the actions of doing intelligible mathematics” (Lynch, 1992, p. 230). Because of the focus on situated activity, this inherently implies that it is impossible to produce a complete and determinate representation of mathematical activity by mathematical formulae or concepts. To account for this lacuna, some educational researchers have begun to focus on inscriptions, the mediated practical use of (mathematical) representation (e.g., Meira, 1995; Roth & McGinn, 1998).

In the emergence and evolution of science, representational practices played a central role (Edgerton 1985). Among the representations, Cartesian plots and line graphs are dominant in terms of their frequency (Roth Bowen and McGinn 1999) and in terms of the rhetorical power ascribed to them (e.g., Bastide 1990, Lemke 1998). A small number of studies analyzed graph interpretations occurring as part of scientists’ and technicians’ ongoing work. These studies suggest that graphs provide perceptual access, ways of

seeing the “natural objects” that scientists are interested in, while at the same time shaping what is there to see (Garfinkel, Lynch, & Livingston, 1981; Goodwin 1995; Woolgar, 1990). In scientific practice, the natural world and graphs had not just become isomorphic (“fundamental structure \longleftrightarrow mathematical form”) but in fact had become fused. When scientists are asked to read on of their own graphs, they articulate considerable understandings of the entire research process that had led to the graph (Roth, Bowen, & Masciotra, in press). Graphs refer not only to some natural phenomenon but stand in a metonymic relation to the entire research process that led to their construction (Roth & Bowen, 1999b). That is, when students and scientists are asked about the meaning of a graph that they had constructed, they tend to talk a lot about natural phenomena, about data collection and transformation, and only a little about what the graph signifies.

There are few studies of the trajectories of increasing graphing competence; the few existing studies (Moschkovich, 1998; Nemirovsky et al., 1998) analyze graphing in interview situations. Such situations represent very different activity systems—characterized by their own mediational relations (see Figure 3)—from naturally occurring ones such as work or self-directed inquiry (Roth, 1996; Williams et al., 2000). Furthermore, there is little research that attempted to understand knowing and learning related to graphs by professional scientists working in situations of uncertainty. In this study, we document how scientists come to the point where scientists no longer distinguish graphs and natural objects, although initially, they had used other graphs and mathematical tools to assist them in their interpretive work.

STUDY CONTEXT

This study is part of a larger project designed to understand knowing and learning related to graphs and other mathematical inscriptions in science. As part of the larger project, we studied the daily graph-related activities of scientists and advanced science students in the course of their discovery work (e.g., Roth & Bowen, 1999b, 2001) as well as activists and technicians in their everyday environment-related activity (Lee & Roth, in press; Roth, in press). This study took place in an advanced laboratory concerned with features of vision in fish; every data run yields several graphs, which are often transformed and always are interpreted on line. That is, graphs constitute a pervasive feature of this laboratory.

Laboratory Environment, Research Focus, and People

The research group featured in this article is interested in better understanding various aspects of the life history of salmonid fishes on the Pacific West Coast of Canada. The group has specialized on the visual system of these fishes, its uses, and the changes it undergoes throughout the life cycle of an individual. An important aspect in salmonids is their migration from the rivers where they hatched to the salt water feeding grounds and back to their spawning grounds in the same river systems that they had earlier left. Researchers have found that just prior to seaward migration, salmonids change their pigment composition from a freshwater to a seawater form. The group is interested in measuring the changes in visual pigment conditions in the rods and cones of the retina over time, along with changes in other physiological characteristics such as silvering of the scales or modification of gill epithelia.

As part of the research pertaining to the fishes, the research group also designs new apparatus. For example, they designed an apparatus to increase the speed with which the data are collected or to improve the quality of the signals that they measure from the natural object (here retina). During the initial three months of my stay in the laboratory, the team was working on the data to be published together with a description of the apparatus. These processes of improving instrumentation cannot be separated from the research concerning fishes. Both lead to the same kinds of laboratory activities, though the publications will focus on one issue or the other (instrument, fish). The videotapes used here were recorded while the research group was collecting the data for a specific article. In this article, the scientists presented their apparatus, which decreased the time of measurement from approximately 20 seconds down to the order of about one second (500–1,200 milliseconds).

The entire experiment is conceptually presented in Figure 4. To maintain the retinal tissue in an active state, the fish has to be kept in a dark container for a minimum of two hours. Because of the light sensitivity of retinal tissue, the experiment has to be conducted at very low intensities of red light—which requires the researchers to dark-adapt themselves for a period of 30–60 minutes. The fish is anaesthetized and, immediately before removal of the eyes, sacrificed by severing the spinal cord. After removal, the eyes are bisectioned and the retina removed. Under the microscope, the researcher cuts one piece, which he mounts on a slide whereas the remainder of the retina is stored on ice in a saline solution. From here on, the retinal pieces are handled only under infrared illumination.

The retinal piece on the microscope slide is then macerated using surgical knives and under an infrared microscope, the image of which appears on a small monitor. After this, adding some saline solution, covering the preparation with a cover slip, and sealing the preparation to prevent evaporation of the solution completes mounting. From here, the slide is mounted in a second microscope fitted with two light sources, one for the stimulus (xenon) the other, an infrared lamp, for providing the background illumination to search for the objects of interest (Figure 4).

Conceptually, the measurement unfolds as follows. In order to obtain information about the photoreceptors in the retina, two measurements have to be made. In the first, a light pulse is made to traverse the slide at a spot where there are no cells (the person operating the microscope asks to take a “reference”). In the second, the pulse is made to go through the cell (the person operating the microscope asks to take a “scan”). Because more light is (normally) absorbed in the cell than in the surrounding saline solution, the difference in the two light pulses is attributed to absorption in the cell. When a blue cone, for example, is active, then light in the blue part of the spectrum is absorbed. On the other hand, if the cell was bleached—previously deactivated by chemical transformation of light—a different absorption spectrum would be observed.

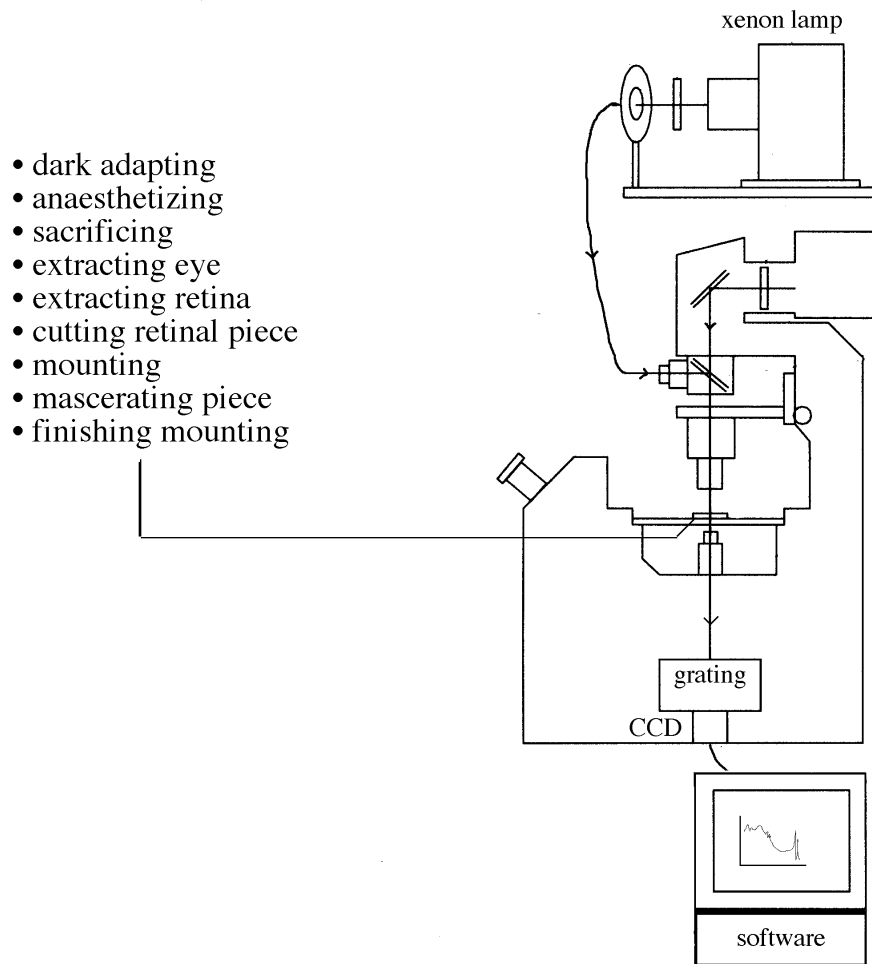


Figure 4. Processes in the preparation of the microscopic slide of salmonid retina and experimental apparatus that produces the graphs based on rods and cones identified and aligned through the ocular or CCD-based optical system. A second CCD acquires the light dispersed by the grating (bottom), thereby allowing a comparison the light spectrum transmitted through the object of interest and a reference.

The experiment is set up such that one person could both align the preparation with the beam of light and operate the computer (counter and data recording), the scientists practice division of labor. This division does not only increase the speed with which the data are collected—excised retina is viable for only one hour—but also contributes to collective interpretations made on line. Thus, one scientist is responsible for searching suitable cells in the preparation, to align the slide for experimental and control measurement, and to manipulate the various shutters and light sources (background,

stimulus) involved. The other scientist operates the data acquisition device (charge-coupled device or CCD detector), infrared camera (for taking images of the cells), and the plotting software through a computer interface he had designed and written.

Laboratory Participants and Projects

The lab is headed by CH, a senior researcher and full professor in biology, with a publication record that spans more than 20 years. During this time, his research was focused on salmonids and vision, the topic that was also at the heart of the experiments analyzed here. CH has been successful throughout his career in many respects. He has received a number of awards and fellowships, has obtained continuous often multiple-concurrent funding from national agencies, and has a substantial publication record.

The second person on the team is TH, a research associate with a background in physics. Before working in the vision lab, he had worked for a small company developing software for CH's apparatus. When CH was able to garner sufficient funding, he hired TH on a fulltime basis to develop apparatus and data analysis procedures, conduct data analysis, and participate in experiments and writing for publication.

As part of an interdisciplinary research project on the socioeconomic changes of coastal communities, which has as its goals to identify alternative ways of securing the survival of these communities, MR became part of the laboratory group. The overall goal of our subproject was to better understand the interaction of local (indigenous) and scientific knowledge with respect to the life stages of salmonids. MR not only observed but also underwent something like an apprenticeship to participate in the biological side of the research. As a physicist and statistician, MR was familiar with the concepts of

absorption spectra and how to obtain them and with many of the data transformation techniques used in the laboratory.

Data and Analysis

Throughout the initial part of the research, MR videotaped laboratory sessions in real time and kept fieldnotes. These videotapes were transcribed verbatim, enhanced by images of the graphs presently being talked about that were copied from the videotape. Subsequently, the tapes were analyzed, annotating the transcripts where appropriate, and attempting to model mathematical procedures when it was unclear just what was going on. For example, CH and TH talked about rotating a particular type of graph. However, whereas MR expected a clockwise rotation of the graph to lead to a movement of a graphical feature to the right, the actual movement observed on the monitor was to the left. By modeling the “rotation” both as mathematical rotation and as eliminating a linear trend, MR ascertained that the CH and TH “meant” to talk about “detrending” as the subtraction of a linear function from the data displayed.

Analysis of the videotapes followed the principles of Interaction Analysis, an “interdisciplinary method for the empirical investigation of human beings with each other and with objects in their environment” (Jordan & Henderson, 1995, p. 39). Interaction Analysis is based on the assumption that participants in interaction make available to each other, and therefore to the analyst, their own knowing and learning and the fact that knowing and learning have occurred. That is, knowing and learning are treated as processes that occur in interactions among members of particular communities rather than in the heads of individuals. In our interpretive approach, we resist after-the-fact explanations that draw on intentions and rationalizations and stay with interpreting what

participants in a situation made available to each other. For example, the opening vignette included the following exchange.

MR: Is this a UV cone?

TH: I think there is a potential hump here [*on right shoulder*] and a little hump there [*next to major peak*] but it is very hard to read.

As analysts, our interest is not in the possible mental content of MR or TH. Rather, our interest is in how the participants hear and subsequently respond to each other's turns. Although MR does not make specific reference to the graph or the object currently under the microscope, TH treats the utterance as a question about the graph. He pointed out that there are two potentially significant humps *and* that the graph is difficult to read. In his response, TH makes available to the MR and the analyst that there are two features salient and that neither one stands out as a clear signal. Rather than imputing something to their minds, the analyst goes by and interprets what each makes available, audibly and visibly, to the other.

Our research is concerned with actions and operations during real time activity—rather than talk about actions, operations, and activity. To represent actions and operations of real-time (student) laboratory activity, we already presented a graphical means (Roth, McRobbie, Lucas, & Boutonné, 1997). These graphical depictions, however, often become unwieldy. In our recent work (Roth & Bowen, 1999b), we used an operator notion analogous to quantum mechanics, in which each operation or action is represented in the form of a mathematical operator. Thus, if after a series of actions $A_1, A_2 \dots A_n$ (preparation), the researcher makes a measurement (O), some property “a” is observed:

$$O \cdot A_n \dots \cdot A_2 \cdot A_1 \cdot x = a \cdot x$$

Hereby, it is unimportant what the “true” nature of the phenomenon “x” is—for example, physicists are no longer concerned with the question whether light *is* a wave or a quantum. Rather, they know that with one series of actions followed by a measurement they observe wave properties, with another series of actions and measurement they observe quantum properties. This way of representing laboratory work is consistent with our theoretical framework, according to which “facts” are the outcomes of human activities (actions, observations) rather than existing independent of human activity.

OVERVIEW

We begin our report by analyzing a sequence of graphical analysis as it occurs in the process of data collection (Online Graphical Analysis). This analysis raises several issues that are subsequently elaborated in greater detail. Interpreting refers to the dialectical process by means of which a sign (e.g., a graph) and a referent (e.g., a natural object) are set into a mutually constitutive relation (Roth & Bowen, 1999a). However, the arbitrary and culturally contingent nature of signs makes the work of establishing the link a non-obvious process. In *Continuity of the Object*, we articulate the work that results in an isomorphic relationship between graph and natural phenomenon. Second, an important aspect of graphical analysis are the transformations that turn real signals coming off the instrument into representations more easily interpreted, acceptable, and convincing. For making decisions whether a graph presents a fact about their natural object or an artifact of experimentation, the scientists have available a range of tool for transforming the data. These tools are also used for working raw data to make them suitable for publication; the

transformed data show the presumed mathematical properties of the phenomenon without the clutter that characterizes raw data. In the section Transformations, we describe the work that turns noisy data into better representations of the laws said to underlie the phenomena. Third, we focus on changing forms of activity as a way of describing individual and collective learning in the laboratory, understood as an activity system. In some instances, previous research results are incorporated into existing (computer) tools; in other instances, scientists learn to “see through” the clutter of raw graphs and recognize without drawing on their tools and transformations whether they are dealing with fact or artifact. We interpret this “seeing through” as a case of internalization, a case where tool-mediated actions have descended to become operations, a form of tacit knowing-how that requires no attention.

ONLINE GRAPHICAL ANALYSIS

Experiments are complex events that are difficult to get a sense of unless one has participated in a series of them. To allow readers a sense for the phenomenon of interest, the online interpretation of graphs as these are being produced during the experiment, we present and analyze one data run, that is, the collection of an absorption spectrum from one cell. In this one run, we articulate a host of issues related to the online interpretation of graphs in experimental science. These issues are taken up in greater detail in subsequent sections. First, what was salient in a graph differed between scientists. Such differences existed not just between insiders and outsiders (such as MR during the initial stages of the research) but also among more experienced members of the lab. Which features pertained to the natural object under investigation was not a priori self-evident from a graph. For example, in the opening example, the bent around 460 nanometers was

initially salient to TH whereas a little hump around 380 nanometers was salient to CH. The difference is that in the first instance, scientist have to conclude that the object of interest is absent whereas in the second case they may see the signature of an UV cone. Second, whether the graph showed something of interest arises out of a process of stabilization in which apparatus, object, graph, and existing graphs become aligned. This alignment involved multiple observations of the object (through microscope or CCD and in graph), transformation of the acquired graph so that it begins to resemble another graph already accepted in the community (and therefore a cultural object). These scientists used multiple forms of transformations on the data such as pixel shifting, detrending, and comparison with normative curves; they “bleach” the object to acquire yet another graph against which the acquired graph can be compared. Finally, there are other transformation processes involved not evident from this transcript. For example, the identification of λ_{\max} (wavelength at which curve has a maximum) and half-bandwidth (width of curve at half its maximum height) is not made from the modified graph. Rather, the resulting graph (the one with appropriate baseline) was approximated by a “Fourier transform fit,” from which the relevant values of λ_{\max} and half-bandwidth were determined.

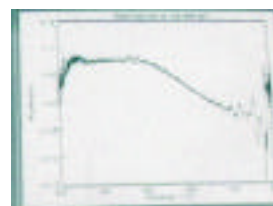
The Session

Data runs begin with the measurement of the control spectrum taken several micrometers away from the target cell. The senior scientist CH—who had prepared the slide, manipulated it under the microscope, and operated the shutters and light sources (see Figure 4)—requested a reference spectrum.

- 01 CH: Ref
02 TH: Ref done
03 CH: Scan (pause) Looks like a single cone.

TH announced that the reference had been recorded, which allowed CH to move the slide to bring the cell into place (with beam turned off). Once the cell was aligned, CH requested a scan and described the cell as a “single cone” based on his visual inspection. Readers should note the hypothetical nature of the description (“looks like...”) and the anticipation of the possibility that the object might turn out as something else (e.g., double cone, broken rod). The software is set to display immediately the absorption spectrum, that is, the difference between the two spectra taken through and next to the cell. Observing the monitor to check whether something of interest appears in the graph, TH announced a “first problem” (Line 04).

- 04 TH: It’s very wide, that’s the first problem.
(*continues transforming*)

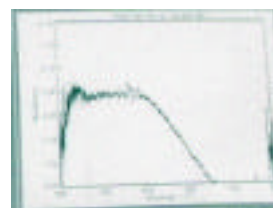


As he manipulated the display, which involved limiting the horizontal wavelength axis below 300 and above 800 nanometers and adjusting the vertical scale to magnify the displayed graph, he provided a description “it’s very wide.” For the non-initiate in the laboratory, it is probably difficult to ascertain the referent of TH’s description. If there had been a feature that noticeably stood out, the non-initiate might have attributed the statement to this salient feature. Although the display showed some features near the left

and right boundaries, these did not appear to be “very wide.” There seem to be more problems (“first problem”) but these are neither articulated nor evident without knowing more about the retina itself. Thus, whereas CH announced the presence of a “single cone,” TH did not see a signal that would count as evidence for it. In such situations, the results of the two observations do not stabilize each other leaving uncertain the nature of the object under the microscope and the meaning of the graph.

In response to TH’s assessment that there are problems in the display, CH raised the possibility of a relative signal (“little peak out there”).

05 CH: What’s that little peak out there in the...



06 TH: This one right here (*points with cursor*)?

07 CH: Too short?

08 MR: About 3-40

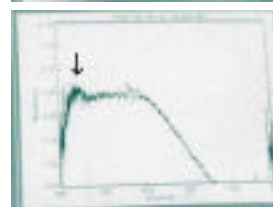
09 CH: Yeah, too short.

10 TH: Yeah, too short.

11 CH: See where I am here. (*Looks through*

12 *microscope.*) Off!

13 TH: Off, Right.



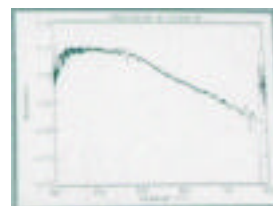
TH was uncertain about the referent of “that little peak” and by pointing the cursor to a small feature in the UV part of the spectrum requests confirmation that both of them are aligned to the same peak (line 06). CH asked whether it is “too short.” Although the nature of “it” would not be clear to a casual visitor, those present know that CH was

talking about the location of the peak along the wavelength scale on the horizontal axis. Sitting close to the monitor, MR responded “about 3-40,” the laboratory shorthand for “340 nanometers” on the wavelength scale. CH both responded to his earlier question (line 07) and thereby disconfirmed the hypothesis that it implied. After TH’s confirmation, CH moved to assess the position of the cell with respect to the stimulus. Looking through the ocular, he suggested that cell and path of light were no longer aligned (“Off!”).

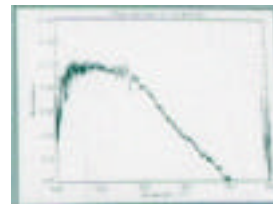
This small episode already allows us to get a sense for the fact that reading graphs online during scientific experiments is not as straightforward as expert-novice and other research on graphing often portrayed it to be. Rather, we observe the scientists engaged in assessing various (yet to be disclosed) features rather than discarding the graph out of hand as not at all portraying the target object. The problematic nature of the graph became more certain only after CH checked the position of the stimulus and notices that it had moved off the cell. What cannot be known is how long the cell had stayed in place, absorbing some of the light pulse, and therefore leaving its characteristic signature on the graph. After noticing that the cell and light cell were out of alignment, the data and its interpretation were abandoned without leaving open the possibility to do more with the data. Without further deliberation, CH requested another scan.

14 CH: Scan... Definitely looks like a single cone.

15 MR:Hmm?



16 TH: It's rather high, in the 4-60 again.



17 MR: Yeah.

In this case, we notice that CH did not request a reference. Rather, the scientists would take the reference from the previous trial. CH did not request a new reference, which indicated that he either attempted to take a measurement on the same cell or on a cell in the vicinity, so that the previous reference remains appropriate. His affirmation that the cell “definitively looks like a single cone” suggested to the other participants that CH had realigned the earlier cell. Both assessments of the resulting spectrum (lines 15, 16) raised doubts. MR’s utterance suggests that he do not recognize an identifiable feature and TH described the feature salient to him as “rather high, in the 4-60 again.” From this utterance, it can be inferred that the feature salient to TH lay near the elbow in the second quarter of the graph, that is, near 460 nanometers on the wavelength scale. His “it’s rather high” suggests the existence of a reference—a peak at 460 nanometers is rather high relative to the “single cone” announced by CH, which should be represented by a peak around 370 or 430 nanometers. Because of this discrepancy, the natural object under the microscope and the graph do not stabilize each other.

In order to understand this exchange, readers need to know that CH, looking through the microscope, classified certain features of the visible display as single and double cones. The single cones absorb in the UV (near 370 nanometers) and blue (near 430 nanometers) part of the spectrum. Each double cone consists of a green- (near 520 nanometers) and a red-absorbing cell (near 575 or 623 nanometers, depending on life

stage). Thus, when TH perceived a possible feature around 460 nanometers, it is incompatible with CH's assessment of a single cone, which should be considerably lower on the wavelength scale. TH's assessment of "4-60 again" suggested that one of the other, here not articulated problems related to the position of the feature salient in his perception.

The next turn showed that this graph was more complex than it first appeared and required further inquiry. CH asked TH to "do a pixel shift" because, as he said, he thought that the peak was not where TH presumed it to be.

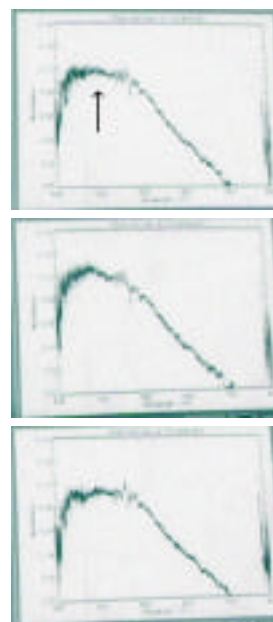
18 CH: Well, do a pixel shift, because I think that one

19 *(points, indicated by arrow)* is the peak.

20 MR: This one, yeah.

21 CH: Again.

22 TH: That doesn't look like it.



CH's gesture suggested that he saw a feature near the top part of the graph. His request to do a pixel shift indicated that a transformation was required before this feature could be seen more easily. MR agreed, thereby signaling to the other participants that he identified the possible peak CH had pointed to.

What a “pixel shift” involves, why it works, and why it is a (culturally) legitimate way of modifying the graph requires substantial familiarity with the experiment, in particular with the data acquisition devices. After the beam of light passes through the slide, it hits a fine grating which in effect disperses the different wavelengths in the way a prism would do. Being spread across an area, the light waves of different wavelength enter different “bins” on the CCD, each of which leads to a point in the data display. For a variety of reasons, the reference spectrum and the sample spectrum may be shifted relative to each other. The light corresponding to a particular wavelength does not fall into the same bin in consecutive reference and sample measurements. A “pixel shift” realigns the two spectra, which then leads to a change in the absorption spectrum. Of course, the scientists would not know how much, if any, shift occurred were it not for a particularity of the spectrum that gives their assessment some certainty. We return to this issue below.

Without responding verbally, TH began to do a “pixel shift”; then another, and yet another. He then commented, “This doesn’t look like it.” We do not know at this time whether the comment pertained to the process or the product of the modification. CH responded “No, in the other direction.” In the context of his earlier request for a pixel shift and the product of TH’s actions, this response could be heard as requesting a pixel shift in the other direction. It also suggested that CH made an observation confirming TH’s assessment that the outcome “doesn’t look like it.” Because of the subsequent shifts, a peak seemed to emerge more clearly in the area made salient earlier by CH. CH appeared satisfied (“OK” line 28) but immediately requested a different action (“now detrend it”).

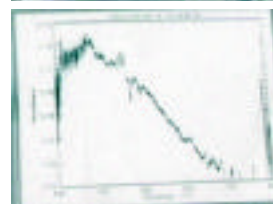
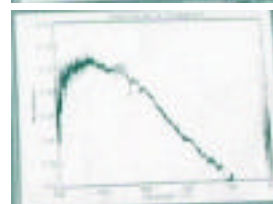
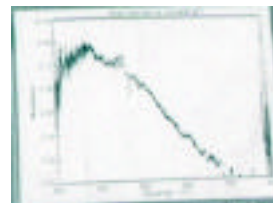
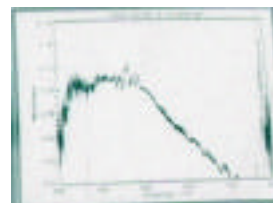
23 CH: No, in the other direction

24 TH: Yeah

25 MR: This one?

26 CH: May be one more. No, the other way. So two
27 that way.

28 OK. Now, detrend it.

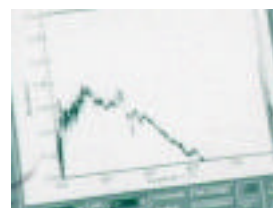


The request is an indication that CH was not yet satisfied. This peak apparently did not correspond to his expectation. Again, considerable familiarity with the laboratory environment and with the phenomena of interest is required. In their publication, the scientists suggested that because of their small size and weak absorbance, the microspectrophotometric data are inherently noisy. In reference to an earlier publication, the article suggested that “if [a curve] showed a clear linear trend ‘tilt’ it was linearly detrended” (JEB manuscript, p. 10). Detrending can be understood in the following way. If in addition to the peak earlier indicated by CH, there is noise increasing or decreasing linearly with the wavelength, the sought-after curve will appear to sit on an inclined plane. Detrending subtracts from the raw data the presumed noise. As an indication for

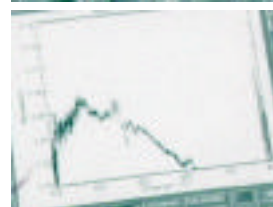
the shape of the noise to be subtract, the researchers took the “long-wavelength limb baseline was uses as the first criterion” (JEB manuscript, p. 10). That is, any detrending had to preserve a horizontal base line of the absorption curve.

As TH began to detrend the curve, MR asked whether they believed the curve to be one with a maximum around 380 nanometers. CH confirmed this all the while encouraging TH to detrend until suggesting that the process of detrending might take more time than they have at their hands. He then made another request for a modification of the graph “Put a 3-80 up.”

29 MR:Do you think it is a 3-80?



30 CH: Yap. Keep on detrending.



31 OK, well, this one can go on forever. (*TH keeps on “detrending”*)



33 But, put a 3-80 up to see what it looks like.

Both, the utterances in lines 29 and 33 suggest that the participants in the laboratory are aware of something that is to be found at 380 nanometers—the UV peak that turned out to be determined in this experiment as having its maximum at 371 ± 9.2 nanometers. But what is the meaning of “putting up a 3-80”? The investigating anthropologist eventually finds out that in the scientific literature there exist measurements of absorption

spectra on other species. There are also available in the scientific literature the coefficients for polynomial functions of degree seven that model absorption spectra. The special-purpose software written by TH makes it possible to plot spectra with maxima at various points along the wavelength axis. In his request (line 33), CH asked to overlay their data with a curve that uses the published parameters. That is, the outcome of prior research (in this or other laboratories), have become incorporated into the set of local tools. Graph interpretation, when it is mediated by these tools, has a definite historical component.

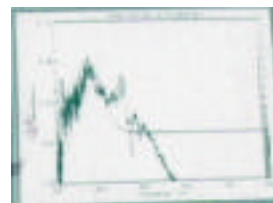
After some problems finding in the dark the appropriate keys, TH succeeded in “putting up the 3-80” and suggested that, in fact, it did fit (line 35). CH showed himself pleased but checked to make sure that it was in fact the “3-80” that had been plotted as a reference; TH confirmed.

34 TH: Yeah. (works on getting 3-80, seeking

35 flashlight) It does fit under 3-80.

36 CH: There you go. 3-80?

37 TH: Yep.



Although this might have appeared to be the end of the process, CH’s next turn indicated that they are not done measuring the cell under investigation. He suggested that they are now “going to bleach it” and asked TH to count. Again, understanding the particular request requires some familiarity with the biochemistry of pigments.

38 CH: So now we are going to bleach it... Ready count?

39 TH: Counting.

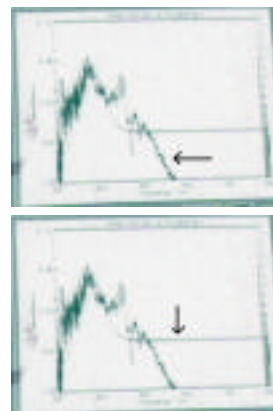
40

When light falls onto a photoreceptor, it is absorbed and its energy provokes a change in the chemical composition. Because of this chemical change, which is not reversed in the excised tissue, the cell is no longer photosensitive. The cell has been “bleached.” The resulting “photoproducts” are sensitive in the UV region. That is, if the scientists do another measurement, the previously visible peak should have disappeared. “Bleaching” can therefore be regarded as an in-situ experimental technique to confirm that a useable peak in fact had been observed, which disappeared as a (causal) result of the bleaching. While the participants were waiting for the bleaching to take place, they continued to talk about the graph visible at the display. First, the utterance “It’s both half-width and lambda max” reflects two observations. The reference curve correctly modeled not only the position of the maximum along the wavelength axis (the same signifier “ λ_{\max} ” [lambda max] is used in different scientific communities) but also the width of the curve at half the height of the maximum. CH confirmed this observation but stated a final problem in this episode. The detrending actually needed to be such that the base line came to be parallel to the reference curve.

41 MR:It’s both half-width and lambda max.

42 CH: Both fit.

- 43 The only problem we are having right now is
 44 the detrending we have got to get this (*points*
 45 *as indicated*)
 46 up there (*points*). I think that that is possible.
 47 Don't you, TH?
 48 TH: Yeah, I think it is possible.



CH suggested that it should be possible to detrend in such a way that the long-wavelength baseline of the measured curve comes to be parallel to the reference. Being requested an opinion, TH, who would be conducting all analyses at a later point, agreed that an alignment of the two baselines should be possible. The scientists subsequently did another scan of the “bleached” cell and, without inspecting it, move on to the search for the next cell to be measured.

Discussion

In this small excerpt from our recordings of online interpretation of graphs in a cutting-edge research lab, a number of issues became salient putting into relief current assumptions. First, whether a graph pertains to a phenomenon of interest or whether it represents noise cannot be established without knowing the entire process by means of which the link between graph and natural object is established. Without knowledge of the series of translations that transform a piece of retina into a peak on the computer monitor, the scientists would be unable to relate on to the other. Second, just what it is in a graph that refers the interpreter to a natural object cannot be taken for granted. For example, line 04 suggests that TH focused on the broad peak was salient whereas CH described the

“little peak” (line 05) as salient feature to be interpreted. Third, the raw data lend themselves very little to making claims about the mathematical properties of natural objects. Scientists learn to clean up their raw data to produce representations that display mathematical relationships. Fourth, in the course of their work, natural objects and graphs stabilize each other, making it appear as if there existed an isomorphism between world and representation. Fifth, as scientists become familiar with these translations, they learn to see whether the raw data contain useful information even without using the transformation tools. That is, the scientists have internalized processes that were initially external and mediated by tools. Interpreting graphs therefore is a historically constituted process. In the following two sections, we provide detailed analyses of these issues. We begin with the a description of the considerable work that goes into constructing the coherence of the natural object across the many translations that it undergoes.

CONTINUITY OF THE OBJECT ALONG A CHAIN OF TRANSLATIONS

If we relax the constraint that nature and its representations are inherently isomorphic then it becomes understandable why scientists need to spend considerable time and effort in translating between consecutive representations of some phenomenon. Latour (1999) suggested that between any two representations of the same natural object, there exists an ontological gap. Any bridging involves arbitrary and culturally sanctioned conventions rather than being able to rest on natural correspondence. Thus, pertaining to our present research, graphs and the natural objects to which they correspond require a lot of work by means of which the correspondence between the two is constructed. This constructive work occurs in time. It is therefore a historical and historically situated process, which is

also a function of the tools currently available and conventions of the scientific community.

Our research shows that laboratory scientists have a concrete model of the object and its surrounding that allows them to navigate their experiment and to establish coherence between the animal and the graph that constructs an aspect of knowledge about it. The model assures the constancy of the phenomenon through the many transformations that occur. In the present case, although the cell itself cannot be seen with the naked eye or even under the microscope that was used to prepare the tissue on the mounting slide, the scientist have a physical model of what happens to a piece of the retina. They “know” where it is located, what particular operations do to it, how this affects the tissue, etc. This coherence is further enhanced by the gestural expressions that they use to show what happens to the tissue when it is pulled or cut, and how the cells are aligned or found when under the microscope. Furthermore, they have models for what is happening on the slide, for example, if there is a larger piece of tissue that separates the cover slide more than normal from the carrier slide so that there is a greater potential for moving about. The movement of the images under the high-powered microscope and the CCD image are therefore explained in macroscopic terms, or in terms of microscopic theories such as Brownian motion, convection, etc.

Contingency of Troubles

Knowing the apparatus and being familiar with each action taken in the preparation of the object is important because from one day to the next there can be variations that initially remain unnoticed. These changes were subsequently “discovered” when the graphs (or images under the microscope) are different from what was expected and from

what had been observed on the previous day. Once they had the sense that something is different, in the graphical representation or in the preparation, they would begin searching for clues to understand what might cause these differences. In the present situation, they had been able to use the new CCD camera connected into the computer monitor to replace “direct” viewing through the ocular on one day. On the next day, however, they could not find their image in the way they wanted.

49 CH: Now, that doesn't seem right. ... Hm... Hm

50 TH: You can change it to a different (*mutters*) then (?) here then we should be
51 back.

52 CH: Hmm, do you remember what it was yesterday?

53 TH: It was this... we didn't change anything here.

The transcript makes evident that there is not only something that “doesn't seem right” (line 49), but that neither scientist knew (lines 52, 53) what was different from the day before. The absence of the image was, of course, troublesome in a double sense: they could not line up their object of interest and, even if they had been possible to do so, they missed a crucial piece in the stabilization of their reading of the graph. They engaged in an extended sequence of activities in order to bring about the visual image on the monitor to correspond to their expectations. That is, the experiment turned out to be troublesome after the preparation had been completed and at observation O_m making it impossible to proceed.

$$O_{m+1} \dots A_{n+1} \cdot O_m \cdot A_n \dots A_2 \cdot A_1 \cdot x = a \cdot x$$

↑

In some instances, the visual inspection (occurring during the search for cells) of the preparation suggests some problem with an earlier part of the preparation or with the general state of the cells. In these situations, the visual inspection serves to stabilize or interrogate a particular transformation earlier in the experiment.

$$O_{m+1} \dots A_{n+1} \cdot O_m \cdot A_n \dots A_8 \dots A_2 \cdot A_1 \cdot x$$

↑ ↑

In the following excerpt, CH links the absence of “fringes” to the way he had chosen to prepare retina—which is actually the accepted way.

- 54 CH: I didn't use a razor blade in the macerating process and I notice
 55 that I don't get those fringes of photoreceptors that... that I have grown
 56 to like somewhat.

At this point, he critically interrogates a change in the practices, preparation, which appears to have brought about a change in what he sees. He does not see the fringes from which cones stick out on a successful day. When these cones were attached to a larger piece of retina, they did not float around and CH can easily take an MSP. In this case, the cells also stuck out horizontally into the fluid and therefore can be identified and used. That is, he changed one of the operations A_i and when he did not find as many cones as he used to, he associated this finding to the change in procedure. The change in the

experimental sequence of actions was associated with a changing visual field (O_m) and therefore was rendered problematic. In the course of collecting the data, the scientists talked about many different factors that could have mediated their success at finding suitable cells. TH might have prepared the MEM solution differently (), the age of the MEM solution (“When did you make up this solution?”), the way he had dissected (“This dissection really bothered me”), the cells have begun to decompose in their solution (“Or it goes into solution, too”), it has been changed by the light (“It’s broadened and looks pretty bleached already”), or just go bad (“viable for only one hour after being excised,” “double cones clearly exhibited signs of degeneration”). In the following episode, CH inquired about the pH of the MEM solution.

57 CH: Was it 7.2 last time?

58 TH: No, 7.42, hmm the same kind, about 200ths different. It was only the time
59 before that I had 7.2.

60 CH: And you made up a full liter, right?

61 TH: Yeah. It’s always one of the jars of MEM.

62 CH: Hmm.

63 MR: Do you see trouble?

64 CH: Well... it’s just that I am not seeing cones and I see rods shrivel up pretty
65 quickly, which means that the osmolarity of the medium is possibly
66 suspect. It’s hard to draw conclusion just now. I just don’t see the number
67 of photoreceptors that I normally see.

Here, CH perceives the photoreceptor cells in a particular way, which he articulates as shriveling up (line 64). Furthermore, the number of photoreceptors was much smaller than the number that he usually observed (line 65). He used this observation as the starting point for an interrogation to ascertain that previous steps in the preparation of the specimen may have changed. Here, the investigation does not identify a possible candidate, for TH appeared to have done everything to specification.

Finding and Modeling the Source of Structure: Signal and Noise?

An important aspect of the laboratory work consists in learning to distinguish signal and noise and in understanding (modeling) the sources of both. That is, scientists have to construct a model that includes both the natural object and potential sources of interference so that they can explain the rather messy data, and develop ways of cleaning up the data by removing only those parts that come from interference effects.

The graphs that come off the experiment shared little with the graphs that ultimately got published, and even less with the smooth lines that enter textbooks. Even a graph that turned out to be “a beauty,” “a textbook example,” or “as good as it gets” exhibited features that scientists have to account for in their publications so that they can be eliminated. They therefore had to find not only the real signal of interest but also came to understand the nature of unwanted features to eventually eliminate them through change of equipment or through manipulation of the data. (TH JUL 18: “This is what I like doing too, looking through the data, too, trying to find reasons for such artifacts [pulling finger along “baseline”]. This is an artifact again, but not as easily explained.”) In the following, specific examples are examined.

A graph as it came off the experiment (Figure 5a) displayed much structure but the real signal of interest was invisible to the untutored eye. The wavelength axis was scaled from 200–900 nanometers. There are strong features in the far-red and infrared region of the spectrum (660–780 nanometers). The scientists did not know the exact origin of the tall peaks between 740–780 nanometers. In one instance, MR asked the scientists about what appeared to be a signal in the long-wavelength part of the spectrum.

68 TH: Well, it is in the deep red.

69 CH: It could be something with the pigment illuminated by the light...

70 TH: The shadows, that you see on the infrared scope there, show that there is

71 some IR absorption not by our pigments, but by something else. But you

72 don't see it.

Here, CH and TH suggested that these peaks come from material that was not visible to the eye because it absorbed in the infrared. On the other hand, when inspected through the infrared microscope, some faint shadows were visible. Because this region lies in any case outside of their interest, they did not worry about knowing the provenance of this feature and cut it off through narrowing the region plotted from 300–700 nanometers (Figure 5b).

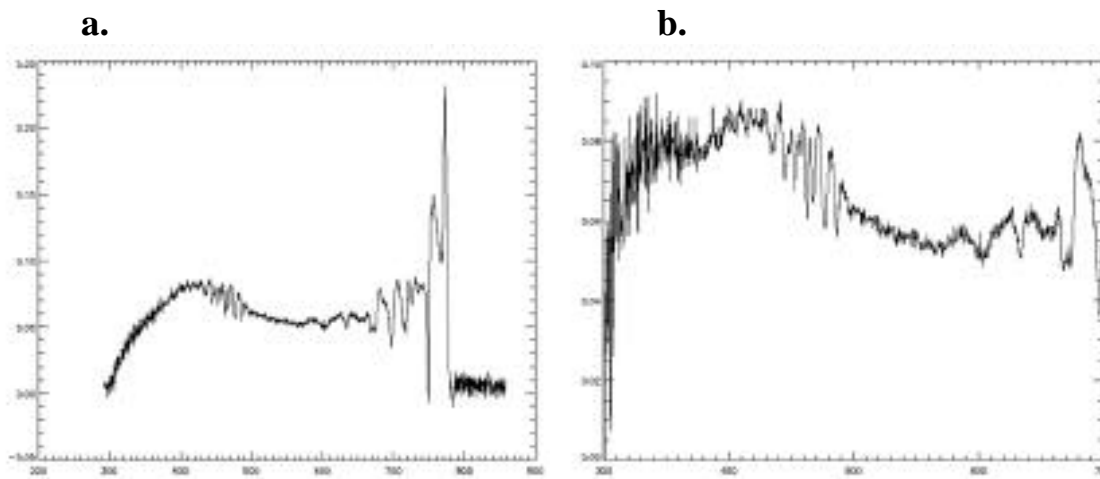


Figure 5. There is much structure in the graphs as they come off the experiment. (a) The unmodified absorption spectrum includes strong peaks in areas not of interest, here, in the long-wavelength part. (b) The same graph as in (a) but with only the ‘region of interest’ displayed still displays structure to be accounted for by the scientists.

After the strong peak had been eliminated and the graph expanded along the vertical axis, there was still “a lot going on in here.” On the left, there were two little humps, the leftmost covered by very rapid changes of counts between neighboring data points. There were two, seemingly extended periodic features, one ranging from 430–490 the other from 560–700 nanometers.

In the course of their work, the scientists had learned that the charge-coupled device (CCD) measuring the light intensity along the spectrum in 5-nanometer interval produced a certain amount of noise even when there was no external light. To reduce this noise, they are held to expose the CCD until its bins are almost filled. However, because the intensity of the light pulses is not constant across the spectrum, the noise will be high where the source output intensity is low—this noise is observed on the left.

It is not that scientists just know about the existence of this noise. They have had direct experience with it in the sense that they saw its signature changing in response to actions that they take.

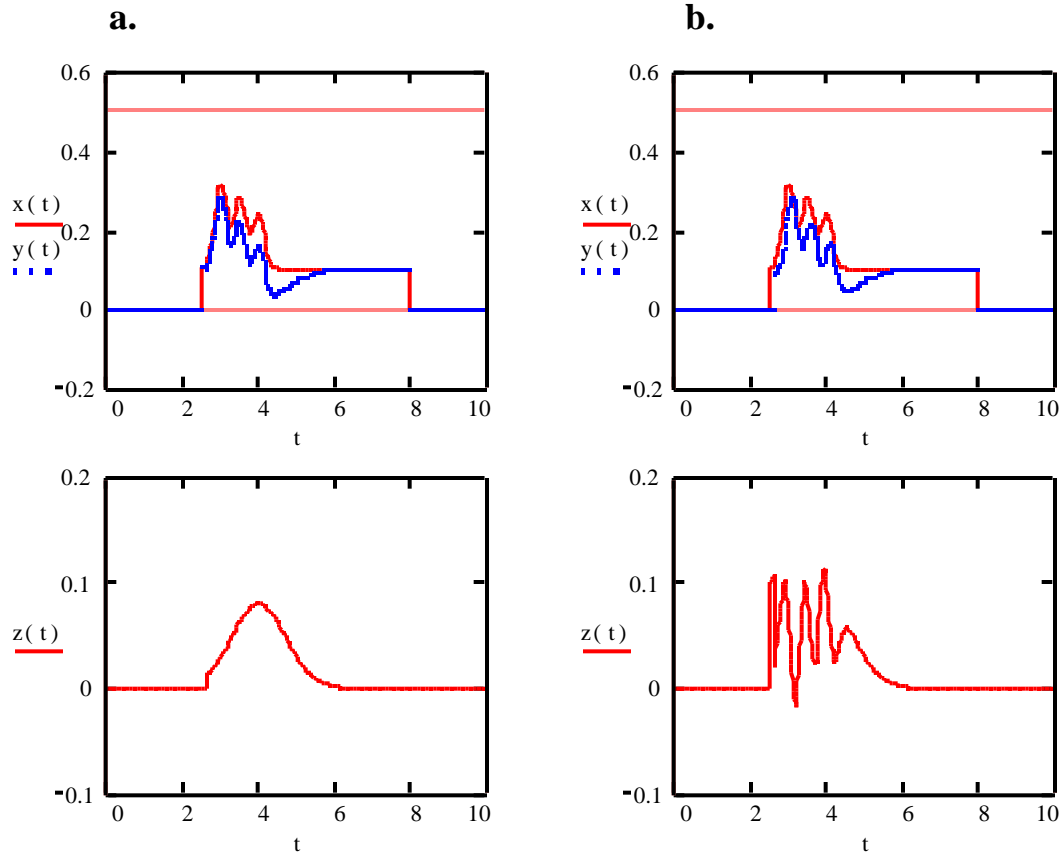


Figure 6. a. If there was only absorption due to the photoreceptors, the difference between the reference and scan signals (each in top diagram) would show the characteristic peak (bottom). b. If the source signal is varied (variation of source intensity, reflection on the cell itself), a ringing becomes visible.

Another feature visible in the graph (Figure 5b) was more resistant to explanation and the scientists spent some time to understand its source and nature. In the region from 430–490 nanometers, each graph taken by the scientists shows a strong “ringing,” that is, a nearly regular oscillating feature. (A similar periodic that constantly shows up is visible in the right part.) This ringing became an important aspect that the scientists attempted to understand and/or eliminate. Because the scientists saw this feature as “ringing,” they conceptualize it in terms of the superposition of two nearly identical signals. TH therefore modeled what would happen if the spectrum of the light transmitted through the cell was slightly shifted. Independently, MR also modeled what would happen if a periodic feature

such as a group of three peaks were slightly shifted or if the signal were changed, for some reason, in its intensity. (According to the anthropological approach, my own modeling efforts turn up the same or similar “ethnomethods” for dealing with the problems at hand [e.g., Livingston, 1995].) Figure 6 shows that in both situations the “ringing” feature becomes visible. However, the two situations differ conceptually and therefore what the scientists can do about them.

In the first instance, the light pulse could be changed through superposition. Each time the light traverses a surface, some of it is reflected (Figure 7). If there are two parallel surfaces near each other, a light beam may experience superposition with that part of itself that has been reflection. The reflection is minimized if the light falls perpendicularly onto the surface and increases with the angle. If the pulse and its reflection are slightly out of phase, that is, shifted with respect to each other, an interference pattern such as in Figure 6a would be observed.

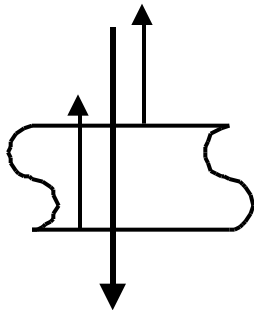


Figure 7. A part of the main beam of light reflects at each surface traversed, thereby decreasing the light intensity. Furthermore, an interference phenomenon is created between the beam and its reflected parts, thereby further changing the spectrum of the light.

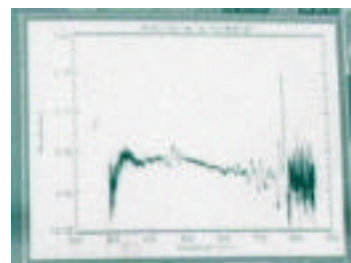
The second assumption pursued is that the “ringing” phenomenon derived from a variation in the intensity of the light. The scientists assumed that the xenon source might

not produce a stable output so that the light intensity varies slightly. In this case, subsequent light pulses have different intensity distribution so that—with or without cell in the path—the ringing can be observed even without a wavelength shift in the light. Such a change in the source intensity would give rise to the ringing, as modeled in Figure 6b. The reflection on the surfaces of the cell would also decrease the intensity and give rise to a ringing due to changes in intensity. This reflection is

At the time that the research was conducted, the scientists thought they understood or had narrowed down the phenomenon. In their research article about the methodology submitted at the time, they wrote that a “light intensity controller was being added “to reduce variability of the signal amplitude across the spectrum” (JEB, p. 9). However, they also suggested that if it turns out that the feature remains despite the addition of the controller, the phenomenon was probably caused by reflection and interference phenomena at the surfaces of the cells of interest. In this case, they would not be able to remove the feature because it is intrinsic to the interaction of the light with the phenomenon under study.

73 TH: OK. Hard to interpret.

74 CH: The (head?) set noise?



75 TH: I don't know. Is it still in position? I have a look in a

76 moment... It doesn't look like anything.

77 CH: Anything in there?

78 MR: I haven't seen anything.

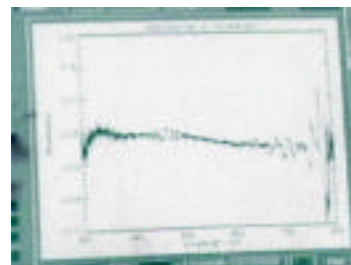
79 TH: It doesn't look like it.

80 CH: Flat-liner.

81 TH: Yeah, flat-liner.

82 MR: Are you still on?

83 CH: I was on. I move on to another.



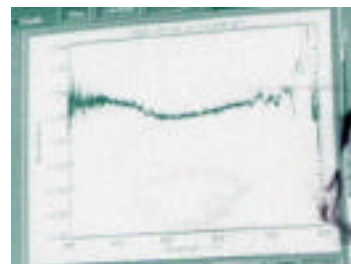
This run began with the request to scan. As this run immediately succeeded a double cone measurement that had shown a clear signal, this lack of a request for a reference meant that this measurement was done on the other member. (Only in very few isolated instances were two different cones measured using the same reference.) This other member, if the first graph was read appropriately, should bear the signature of a red cell. Although a novice in the laboratory may raise the issue that there is a broader peak in the center and a narrow clearly defined peak on the far left, TH looked at the graph in terms of the expected curve corresponding to a red cone. TH found the graph “hard to interpret.” All three could not find the slightest evidence of a peak, which TH and CH characterized as a “flat-liner.”

In this case, an object of potential interest can be observed at one stage (O_m). CH confirmed that he was still on the cell (line 83). However, the expected signal (O_{m+1}) corresponding to the object is missing. The object therefore failed to stabilize. The scientists abandoned their effort regarding this cell and “moved on to another” one.

In the following episode, it is again unclear whether the graph is a good one or not. CH suggested that the object under the microscope looked like an UV cone. He offered two (implicit) hypotheses for the problem of not seeing a clear signal in the graph. First, his “I could try to get in there better” suggests that the cone was not perfectly aligned with the beam. Second, he articulated low amplitude as a possible problem.

84 CH: (*Looking through microscope*) It looks like a UV... to me at
85 least. I could try to get in there better. It could be low
86 amplitude, but I think... I don't know.

87 TH: I save it as a UV but may be we
88 should rescan. The problem is only,
89 yeah, if you could... If you have
90 these photoreceptors in the clear
fluid



91 around. Then this is a problem. The problem is what you have
92 below and above it... Or it goes into solution, too.

The response implied uncertainty. First, TH suggested that he would save the scan “as a UV” but that they could also rescan the cell. He then described two further problems that would not be solved by rescanning: the liquid above and below the cell would still be present and that the cell might have begun to go into solution.

In-Situ Experiment

Doing an experiment in situ is one of the options that these scientists had in ascertaining which part of the graph can be attributed to the photoreceptor. As was described earlier, scientists may decide to “bleach” a photoreceptor. The difference between the first and second measurements can then be directly attributed to the photoreceptors, which have disappeared in the process. That is, they could attribute changes in the graphs to a manipulation of the object, thereby enacting a classical experimental design of the type

$$\frac{O_{m+1} \cdot A_{n+1} \cdot O_m \cdot A_n \dots A_2 \cdot A_1 \cdot X}{O_c \cdot A_n \dots A_2 \cdot A_1 \cdot X}$$

where the temporal sequence of actions in the activity is from right to left. First, the scientists took a “reference,” which they acknowledged as observation O_c . After moving the photoreceptor into the path of light, they take their sample (O_m), which led to the display of the absorption curve $O_m - O_c$. When they decided to bleach, they enacted the operation A_{n+1} (bleaching) followed by another measurement O_{m+1} . Here, the control observation (O_c) is assumed not to be changing until O_{m+1} had been taken. However, the scientists were not even interested in $O_{m+1} - O_c$, though they might occasionally plot it (Figure 8b) but in documenting the change between O_m and O_{m+1} , (Figure 8a) which is attributed to the experimental manipulation (bleaching).

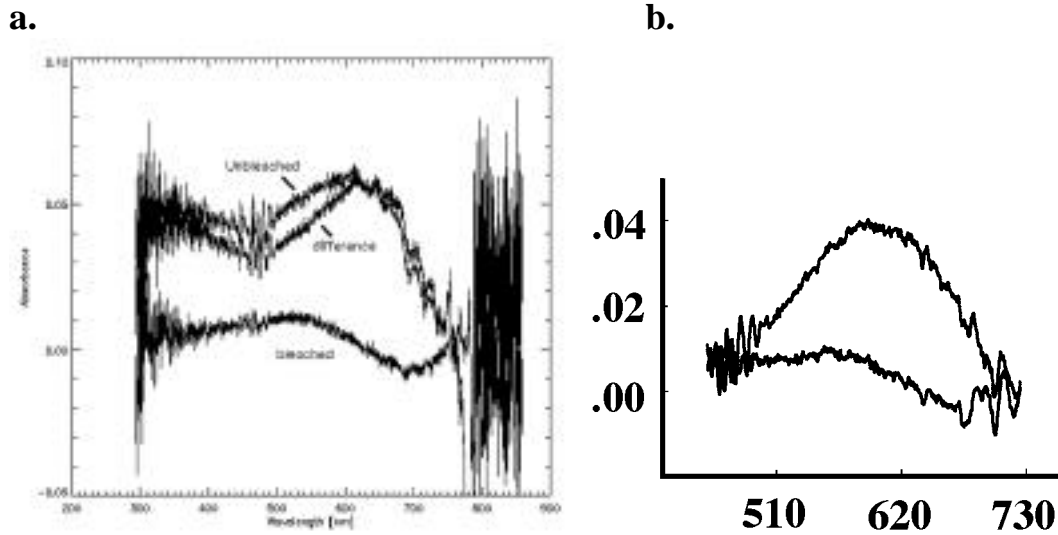


Figure 8. Bleaching changes the signal from a photoreceptor. (a) The difference of the absorption spectra from an unbleached and a bleached gives ‘clear evidence’ for the presence of a red cone. (b) For the publication resulting from the observed data collection sessions, the scientists present a best case for the absorption spectra from an unbleached and bleached photoreceptor. Noticeable is the absence of the noise in the short- and long-wavelength part of the spectrum still present in the left panel.

Summary

The descriptions in this section support the idea that correspondences between natural phenomena and their representations in graphical form are not natural. Rather, substantial effort is required to establish these correspondences despite the continuous appearance of trouble that interferes with this work. Our description articulated the role of a model that explains the coherence of the phenomenon in and through the transformations so that, in the end, an isomorphic relation between nature and representation can be said to exist. One of the tools *these* scientists have available to ascertain the origin of their signal is by obliterating the object of interest (“bleaching the cell”) so that the signal disappears, thereby providing strong evidence that they had in fact observed the phenomenon (fact) rather than an artifact. The existence of model that explains the transformations and sources of interference allows scientists to manipulate the data in an attempt to remove

the effect of random variation and artifacts arising from a variety of sources. We now turn to a description of this work that goes into these transformations.

TRANSFORMATIONS

The data collected by scientists seldom show the smoothness that characterizes functions in introductory mathematics course or the graphs that are featured in textbooks. Through their work with the phenomena and producing smooth curves, scientists gained substantial familiarity with the phenomenon, transformation of data, conceptual surroundings of phenomena, and mathematical transformations and their relations to the scientific phenomena. There was therefore a mutually constitutive relation of the scientific phenomena, the conceptual underpinnings explaining them, the raw data, and the transformations that turn them into publishable data (in support of the conceptual underpinnings). Doing these transformation repeatedly allowed scientists to develop to the point that they decreasingly required transformations to make a decision about the usefulness of a data run. In the end, even hardly noticeable features of a graph were sufficient for interpreting whether a run yielded good or poor data.

The raw data from an experimental run are displayed in Figure 9a. Not only do we observe a very noisy curve but also this curve does not resemble an absorption curve (which often are Gaussian). After the scientists in this study have done a series of manipulations (to be explained below), their graph now shows a much greater resemblance with a Gaussian. This curve continues to be associated with a substantial amount of noise, which is of the order of magnitude of the signal itself (Figure 9b). The data show a lot of noise. The scientists therefore add the data from several runs in order to decrease the noise and increase the signal to noise ratio (Figure 9c). In these last two

curves, scientific readers can recognize an underlying similarity with the solid curve, a “template” that has been accepted as the scientific norm for such data.

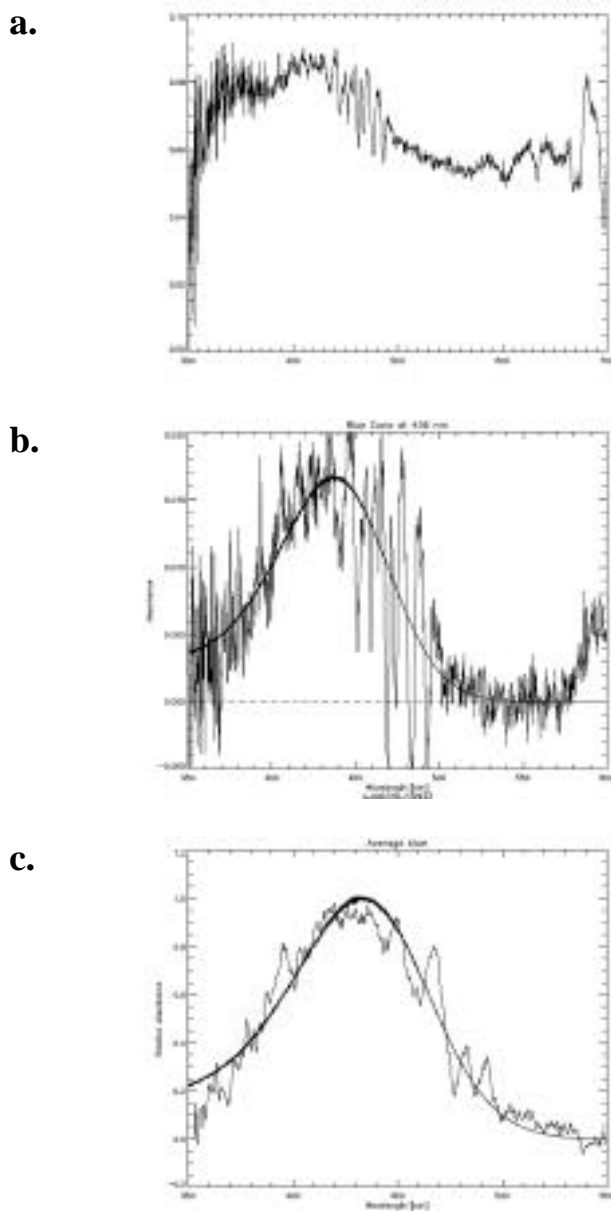


Figure 9. The data of an absorption spectrum are seldom if ever ideal and therefore have to be transformed in order to comply with the expected curves. a. The raw data as they come from the CCD device, but with low and high wavelength cut off. b. Detrended curve fitted with an eighth-order polynomial as previously proposed in the literature. c. Result of averaging 29 curves such as that in (b).

It is this template that scientists see even when looking at a graph such as Figure 9a. All the transformations necessary to go from this graph to the cleaned up version in Figure 9c appear to become transparent so that scientists actually saw that a peak was suitable, provided some detrending, pixel shifting, etc. has been completed. In those instances (red sensitive A_2 cones), the scientists use a particular technique that actually gets rid of the noise. Rather than fitting a curve to the data, they transform and re-transform their data, in the process cleaning them of the (high-frequency) transients (noise). We propose that scientists' understanding of phenomena, graphs, transformations, and instrumentation are all highly inter-related and mediate each other.

In the following, some of the transformations and the mathematical and scientific conceptions that underlie them are presented. Scientists' understanding of the graphs that they produced were inherently mediated by these understandings such that understanding scientists' understanding requires, in turn, anthropologists of science to understand them.

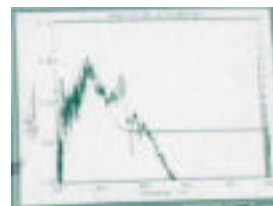
Fitting a Template

Existing graphs strongly mediate the work in the laboratory. Whether a particular graph was a likely candidate to become part of the published data was sometimes determined by drawing on existing "templates." In an already-cited excerpt, CH asked TH to "put a 3-80 up" so that they could "see what it looks like."

33 CH: But, put a 3-80 up to see what it looks like.



- 34 TH: Yeah. (works on getting 3-80, seeking
35 flashlight) It does fit under 3-80.
36 CH: There you go. 3-80?



Here, CH explicitly requested a second graph to be superposed over their already somewhat detrended data. TH put up the 3-80 and confirmed that their graph “does fit under 3-80.” The sample graph with a maximum at 380 nanometers on the wavelength scale functions as a template that, having been published more than a decade earlier, had become the norm in this scientific domain. It is therefore the outcome of an earlier experiment that has become accepted by the scientific community, to become a tool for subsequent research on the absorption spectra in visual pigment. What matters in the complete data analysis is not only the location of the maximum but also the width of the spectrum at half of the maximum height (“half-max bandwidth”).

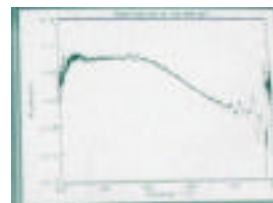
As part of the online interpretation of graphs, these scientists were in the first instance more frequently concerned with the location of the maximum rather than with “half-max bandwidth.”

In the present instance, the computer plotted the comparison graph. That is, an outcome of a previous experiment, accepted by the scientific community, was implemented in the custom software. On the other hand, when the scientists see in Figure 9a usable data, it was because they recognized in it the similarity with a template that could be plotted (Figure 9b). That they had internalized the template to some degree can be seen from the following assessment of a curve that is “very wide”—which in fact is too wide when compared with the template around 500 nanometers. That is, having had

sufficient exposure to different graphs, the scientist no longer needed the template at this point in time.

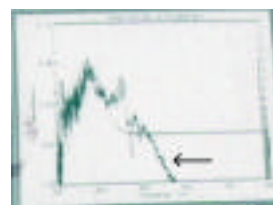
04 TH: It's very wide, that's the first problem.

(continues transforming)

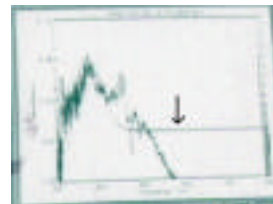


It is when the identification of a peak is more tenuous that the scientists called up the stored templates and plotted them over the top of their own data. This template allowed the scientist not only to find the appropriate max and half-bandwidth but also served as a criterion for the other transformations that they conducted. For example, in the opening episode, CH exhibited concern regarding "baseline compliance," that is, the fact that a detrending had to make the baseline of their data consistent with that of the template.

43 CH: The only problem we are having right now is
44 the detrending we have got to get this (Picture
45 96) (points)



46 up there (points) (Picture 97). I think that that
47 is possible. Don't you, T?



48 TH: Yeah, I think it is possible.

Furthermore, detrending was also constrained by the slope of their curve, which had to be consistent with the slope of the template. If any of these constraints was not met, or

if differences could not be explained such as in the widening of the spectrum with a shift from freshwater to saltwater pigment, “the spectrum was rejected.”

If it was well defined, the spectrum was given further consideration. If it showed a clear linear trend (tilt) it was linearly detrended (Hárosi, 1987). Then a template was fitted to the data. For A_1 based visual pigment cones an eighth order polynomial (Bernard, 1987) was fitted to the absorbance spectrum... (JEB, 10)

Because there are no published templates for A_2 based red-absorbing visual pigment, the scientists used an A_1 template and then used a Fourier transform of their data to show the expected widening and decreasing of the peak with respect to the A_1 pattern. Here, new scientific knowledge was constructed out of the difference between accepted pattern and the new patterns created by this research team. (The publication of this work has to await further investigation, not the least because the (biological) mechanisms underlying these shifts are not understood and therefore require substantial investment.)

Fourier Analysis

In the following excerpt, MR was talking to TH about the results of his analysis pertaining to the red cones (Figure 8).

- 93 TH: The better the shape (gestures along shape of curve) the better FFT works.
94 So I actually have for the broad, where it has the A_2 pigment, where I do not
95 have such a template, not for the A_2 , for the red I have the FFT going
96 through it. And it fits perfectly. That works rather well the better the shape
97 is but it definitely works well for the average [of all reds]. You see this is a

- 98 single red measurement (Figure 8). Because A_2 has a larger bandwidth and
99 the red (bold smooth line) is the A_1 template. And this is the difference...
100 (Points to the difference between narrow and bold smooth lines.)
101 MR: So you probably have some mixture?
102 TH: This is an A_2 more or less. This is what we are trying to get to. So it is
103 slightly lower and slightly wider and this is exactly the effect we are looking
for.

Here, because templates for the widened A_2 peaks did not yet exist so that measure the bandwidth after doing a double Fourier transformation (FFT and iFFT), removing the transients in the process.

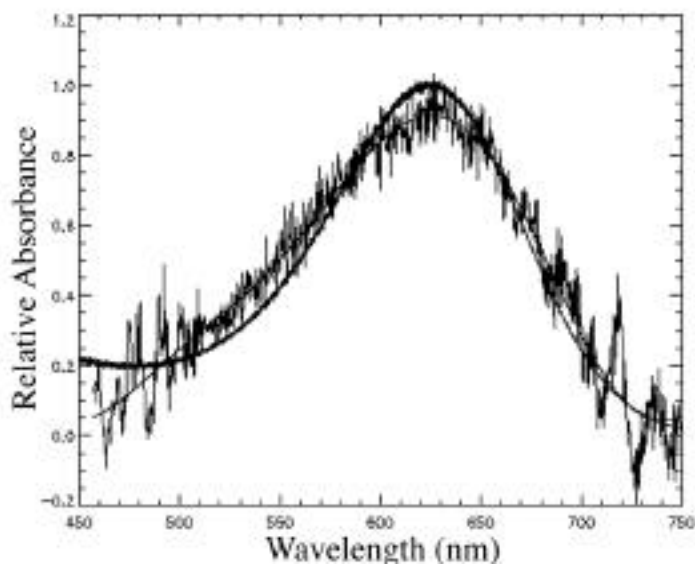


Figure 10. Scientists do not just fit their data using the published eighth-order polynomial template, but also apply a FFT procedure to get rid of the noise in their data.

In this situation, the data averaged over about 8 red cells appear to be described quite well by the published eighth-order polynomial (bold smooth line). When they used the

FFT smoothing/ fitting technique, they arrived at the narrow smooth line. Visual inspection shows that the narrow line is wider at half-height. That is, the half-bandwidth is larger. This may be interpreted as a problem for the methodology that CH presents to his peer. However, because he knows that rods change not only ω_{\max} but also the half-bandwidth of the signal when the salmonid changes from the freshwater to saltwater form, this change in half-bandwidth is taken as a positive sign that similar changes exist for cones. In some situations, information such as the estimates of the mean half-maximum bandwidth is actually taken from the Fourier transform fit.

The scientists' understanding of the relationship between the smooth curve and the original data is mediated by the transformations, including the Fast Fourier Transform and its inverse. Utilizing the Fourier transform therefore cleans the signal of undesirable noise but does not fundamentally change the data other than eliminating transients. Fitting the curves using some higher order polynomial does not have the same equivalent, unless the curve conceptually, that is, theoretically, should have the form of a higher order polynomial.

Take the following instructive example. Consider a true signal with a Gaussian shape similar to the one our scientists expect that is riddled with random ("shot") noise (Figure 11a). A Fast Fourier Transform (used with discrete data points) provides a set of coefficients displayed in Figure 11b. If these coefficients were used in the inverse FFT, the original data would be reproduced. If, however, the coefficients corresponding to high-frequency sine curves are set to zero (here all coefficients but c_0 to c_4), a smooth curve approximating the original data is produced (Figure 11c).

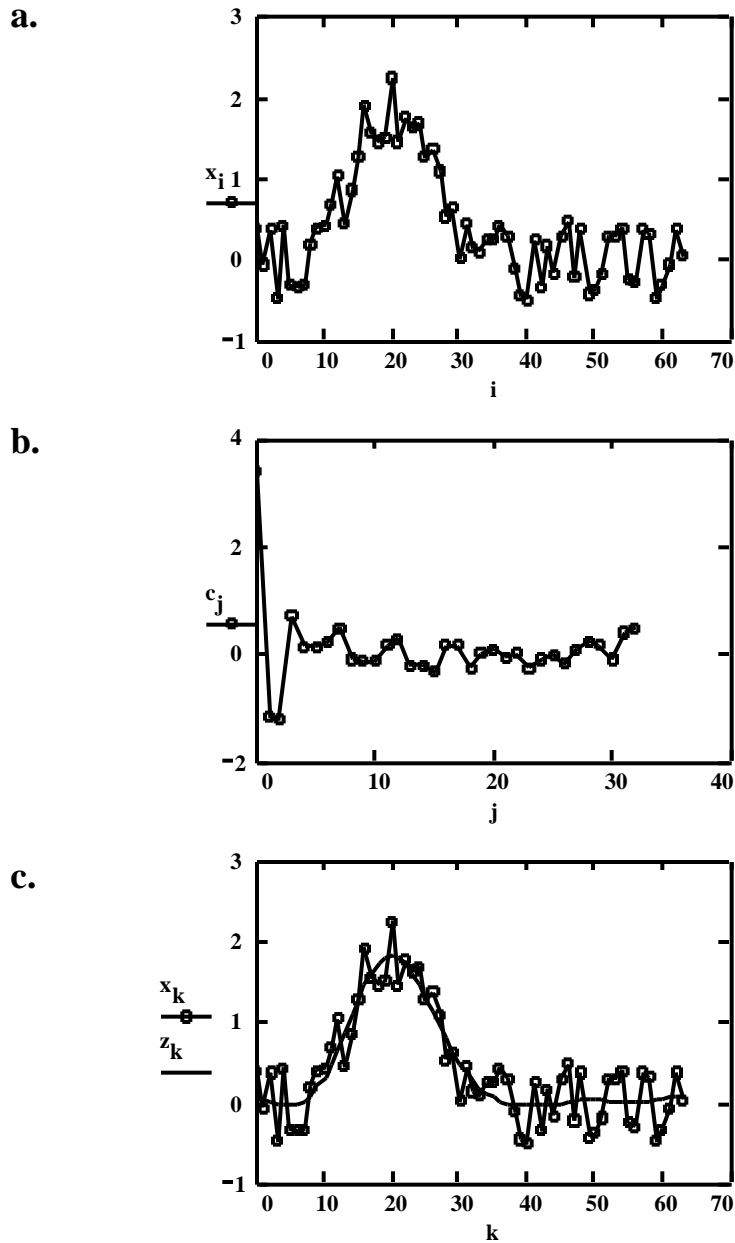


Figure 11. The Fast Fourier Transform is used to smooth and fit a noisy curve. a. Gaussian with white (random) noise. b. The coefficients of the Fourier-transformed original curve. c. All but the first five coefficients are “lopped off” (set to zero) and an inverse Fourier transform is performed, a smooth curve results.

That is, the graphs exist both in the context of the natural phenomenon and as mathematical objects that can be transformed, smoothed, translated, etc. However, all these transformations have an equivalent in the natural world. For example, the raw data

are thought to be the result of the true absorption curve plus noise, fast transients. By doing a Fourier transformation, the scientists lop off the fast transients that do not belong to the phenomenon. Removing the transients is not just a mathematical technique to make the data less noisy but it also has a physical analogue. In the present situation, the true signal is nearly Gaussian (actually, a higher one for the α -band and a lower one for the associated β -band, which partially overlap). The rapid oscillations are part white (shot) noise from the CCD, in part response of refraction properties of the cell (oscillations around 450–500 nanometers). Both types of oscillation are of rather high frequency compared to the body of the Gaussian. Given that these oscillations are not part of the signal from the photoreceptor they can legitimately be eliminated.

Summary

In this section we provided evidence for the changing nature of scientists' interpretation of graphs. Initially, they used a variety of tools to transform the graphs before making a judgement about its suitability as evidence for the phenomenon that they researched. Over time, the scientists relied decreasingly on these transformations until, about one half year after data collection began, they no longer needed the tools and transformations. Reading graphs, which had started as a tool-mediated action, had become an automatic and unconscious operation; we can say that the process had become internalized.

LEARNING IN AN ACTIVITY SYSTEM

Graphs as objects do not exist as independent entities but are part of complex networks that integrate entities and processes. The competence of a scientific reader of a

graph (relative to its “standard” reading) depends to a large extent on the reader’s familiarity with the entire network of entities. The producers of a graph, therefore, will always show great competence because of their intimate familiarity with the network. Other scientific readers also need to be at least familiar with the phenomenon and know how such graphs are produced and transformed. That is, the reader of the graph has to be already familiar with how such places (laboratories) function, and therefore, how graphs and the phenomenon it is said to stand for come to be associated. The understanding of graphs therefore depends on the stabilization both in the laboratory and its subsequent adoption and distribution in the scientific community (journal), from where they can then be internalized by other scientific laboratories, their instruments and people.

Signs and Referents, Tools and Natural Objects

The interpretations are the results of historical processes in which a system of signifiers and processes stabilizes itself. Results of earlier research by this and other research groups are internalized by individuals or are built into the instruments and calculation devices (computers, software), mediating future interpretations. As a result, what the research shows is a transforming activity system in progress. Some of its historical transformations can be reconstructed or are visible when there is trouble. Especially during the early stages, the scientists frequently used detrending, shifting, and overlaying of templates to make decisions about the suitability of graphs as data in subsequent detailed analyses.

During the scientists’ laboratory work, the graphs that they interpret online are both tools and object in the inquiry. On the one hand, they use graphs as tools to interrogate and interpret the “natural object” and the entire chain of translation by means of which

the “natural object” is made present again. On the other hand, the graphs also become objects of inquiry in their own rights that are interpreted in terms of the scientists’ understanding of and familiarity with the natural phenomenon under investigation and the contributions of the investigative process on the representation. The graphs therefore exist in a dense network of mutually stabilizing entities that also include natural objects, researcher skill in preparation, mathematical transformations, instrumental contingencies, and so forth.

Scientists do not just make inferences that lead them from the sign to the referent. Rather, scientists always move back and forth. Based on the graph, they imagine possible scenarios that could have given rise to the representation; based on their understanding of the natural world, they imagine what a graph would look like given the graphical (representational) space at hand. It is out of the degree of congruence in the results of both movements that scientists develop a sense that they understand. From the activity theoretic perspective used here, we say that the scientists interchange tools (instrumentation, concepts of natural world and instrumentation) and objects. Their sense of understanding arises when tools (graphs) and natural objects (photoreceptor cells) mutually stabilize each other. Even if the inspection through the microscope suggested the presence of a particular type of photoreceptor cell (“definitely looks like a single cone”), an unexpected graph or the lack of a significant peak will turn the earlier observation into an unusable piece of matter. Conversely, an uncertain visual inspection (“a single cone or a broken rod”, “single cone or double cone on the side”) is turned into a definite object by its associated graph.

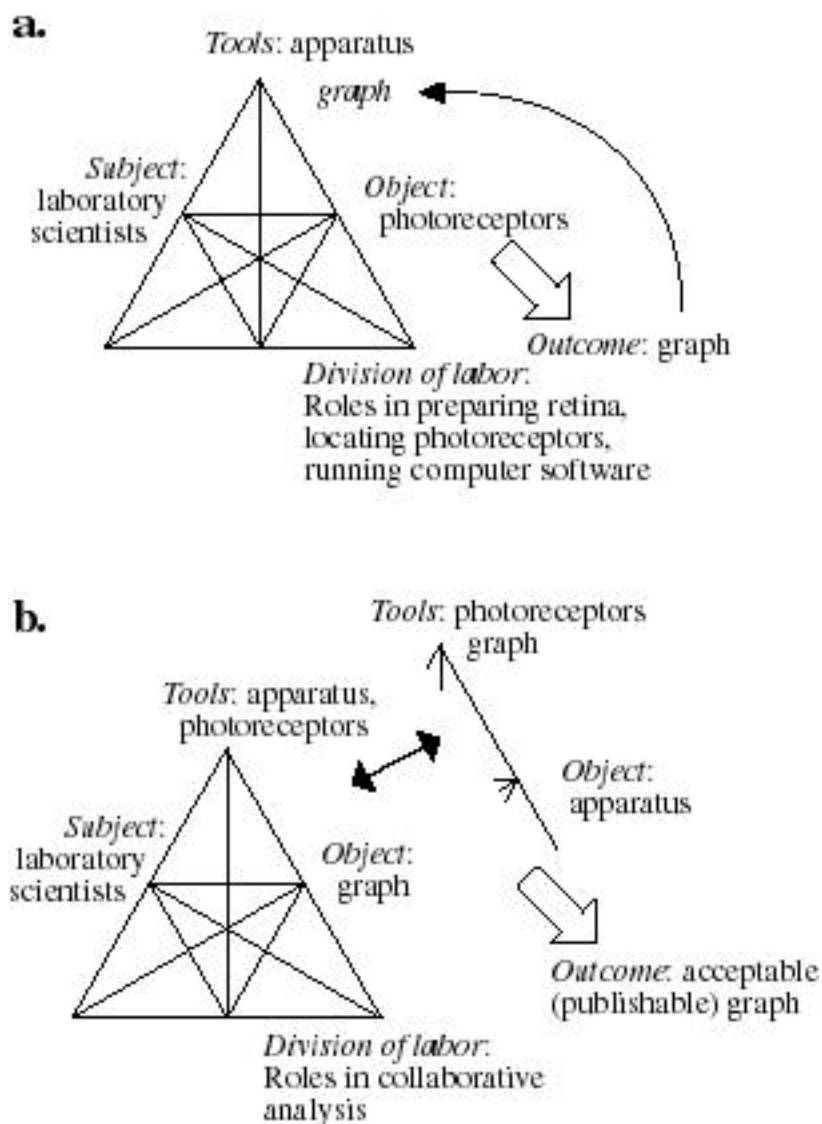


Figure 12. a. As soon as a graph has been produced, it becomes tool or object in its own right. b. The graph then participates in the stabilization of natural object, instrumentation, processes, and representation. The outcome of this stabilization work is a publishable graph.

Although we have charted a very different research itinerary, we have come to descriptions of the relationship of graphs, instrumentation, and conceptual understandings that are quite similar to existing historical analyses (Gooding, 1990, 1992; Pickering, 1992, 1995). Based on his analysis of Faraday's laboratory notebooks, the former suggested that Faraday did not discover the electrical motor and the underlying scientific

theory by making inferences from controlled experiments. Rather, the phenomenon, ability to produce it, and conceptual understanding were involved in a process of mutually stabilization. In the earlier stages of his inquiry, Faraday “was not yet able to make the distinction between the representation and its object” (Gooding, 1992, p. 99). It is only at the end of his inquiry that Faraday came to separate phenomenon, process of inquiry, and scientific theory. “The correspondence of representations to their natural objects is the results of a process of making convergences, both in experiment and in narratives that reify the distinction between words and the world while removing traces of the work that enabled the distinction to be drawn” (Gooding, 1992, p. 99). In scientific experimentation, “gestures, skills, and so on—all of these aspects of disciplined human agency come together with the machines that they set in motion and exploit” (Pickering, 1995, p. 17). Pickering suggested that disciplined human agency and natural phenomena (which he called “captured material agency”) become intertwined in a mutually constitutive manner and therefore interactively stabilize each other.

We gain the least information from those situations when the graph is unproblematic. In this situation, scientists can produce the rationalizations that they have built up in their historical development. However, the same recipe-like explanations are not operative and are not drawn on in the case of trouble. Then, interpretation becomes an art rather than the application of general skills and explicit routines.

Movement of Objects (Graphs) through Activity Systems

After the scientists have stabilized graphs, natural objects, and instrumentation (and associated practices), they use textual and graphical resources to stabilize their graphs (and associated methodology) so that they will fare well in the community and become,

eventually, accepted among the tools available to researchers. The scientists articulated how they drew on legitimized (accepted in peer review and subsequently published) procedures for preparing the natural object (photoreceptor) and for transforming the raw graphs (e.g., templates, detrending, Fourier transformation, and pixel shifting). Explicitly locating their own activity in the concerns and practices of the community guarantees a certain level of success to the prospects of their own work becoming an integral feature of the community. That is, the prospect of bringing about changes not only in their own activity system but also in all the aspects that were also part of the activity system of other research groups. Eventually, the scientists believed that they had sufficiently stabilized their tools and outcomes and that they have produced a text that was not only reflective of the stabilization process but also as unassailable as they can possibly consider. At this point, they submitted their work to a journal and thereby to a peer review process (Figure 13).

Once the article has been accepted (which involves editors and reviewers serving for the community as an aspect of the division of labor) and published, the tools it describes and the graphs and data it presents are ready to become used by other researchers. Being used really means that these research tools, graphs, and data are available and can be built into other tools or be internalized by other researchers (subjects in activity systems). This process of being taken up was evident for the outcomes of other previously published research in the present situation. For example, the eighth-order polynomial curves, outcomes of earlier research, were built into the custom software to be used during the online interpretation as templates against which to judge the graphs produced by the researchers. These templates therefore constitute built-in tools that stabilize or destabilize

a given graph as a candidate for further consideration. However, these eighth-order polynomials were not just built into the software but, having used them extensively, the researchers have become so familiar with them so that they can see in a noisy graph those features that make them match to a template. That is, by looking at a graph they can see it as a candidate—which, however, they have to clean up (detrend, pixel-shift, enter into averaging procedure, etc.) before their peers will be able to see in the published graph what they can see in the messy one.

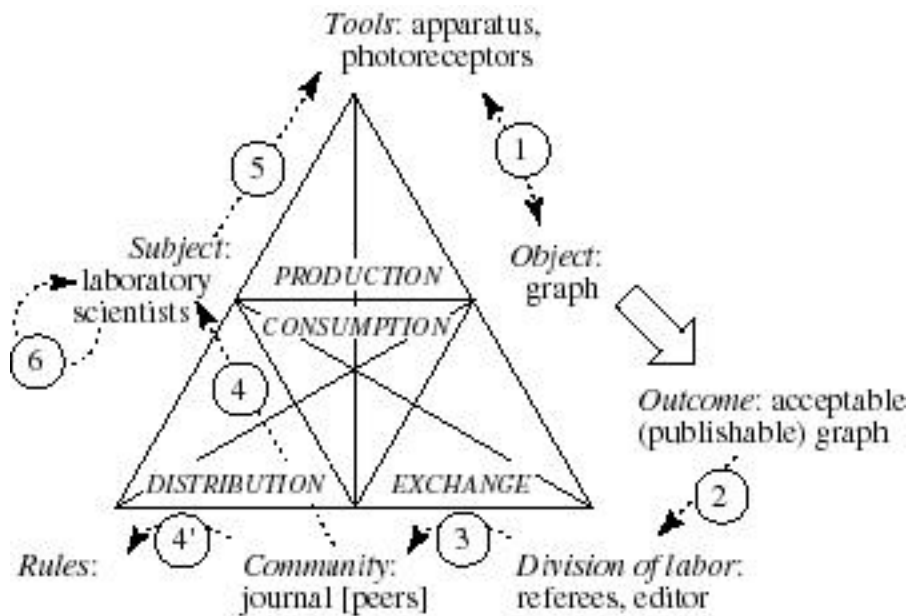


Figure 13. After the graph has been stabilized in the context of instrumentation and natural object (1), it moves via the review process (2) to become an aspect of the community (3). From there, it can be appropriated into a another (or the same) laboratory (4) where scientists begin to use it as a tool (5), build it into another tool (5), or internalize it themselves (6). In their publication scientists also formulate rules for reading graphs or using tools in specific ways (4').

Scientific tools and graphs are never just presented but are always published with detailed instructions of how to use or read them, respectively. That is, scientists do not just present a table with the values of \max and mean half-maximum bandwidth and the

corresponding graph but use main text and caption to constrain the ways in which these can be read.

Graphs do not simply display relationships, adjuncts to text, or proofs for something stated in the text that readers can “take in” in an unproblematic way. To understand the biological phenomena of which the graph is a part, readers must engage in a reflexive elaboration in which the main text and caption provide iterable instructions for where to look and how to read the graphical display; they provide organizational resources to the reader’s gaze and interpretation. But this is not sufficient. To understand the graph, the reader already has to bring an understanding of the biological phenomena and the ways these come to be presented in something like a graph.

Internalization

One of the by-products of collecting data over and over again is the apparent internalization of tools and the outcome of applying them to graphical objects. Initially, and particularly in “difficult cases,” the scientists use the graphing software to produce a reference graph (e.g., “the 3-80”), to “detrend,” or to “pixel-shift” the outcome of a measurement. As an outcome of these actions, the scientists produce a new, more easily interpretable graph that is used to make a decision about keeping the data for future analysis or about deleting the data (Figure 14).

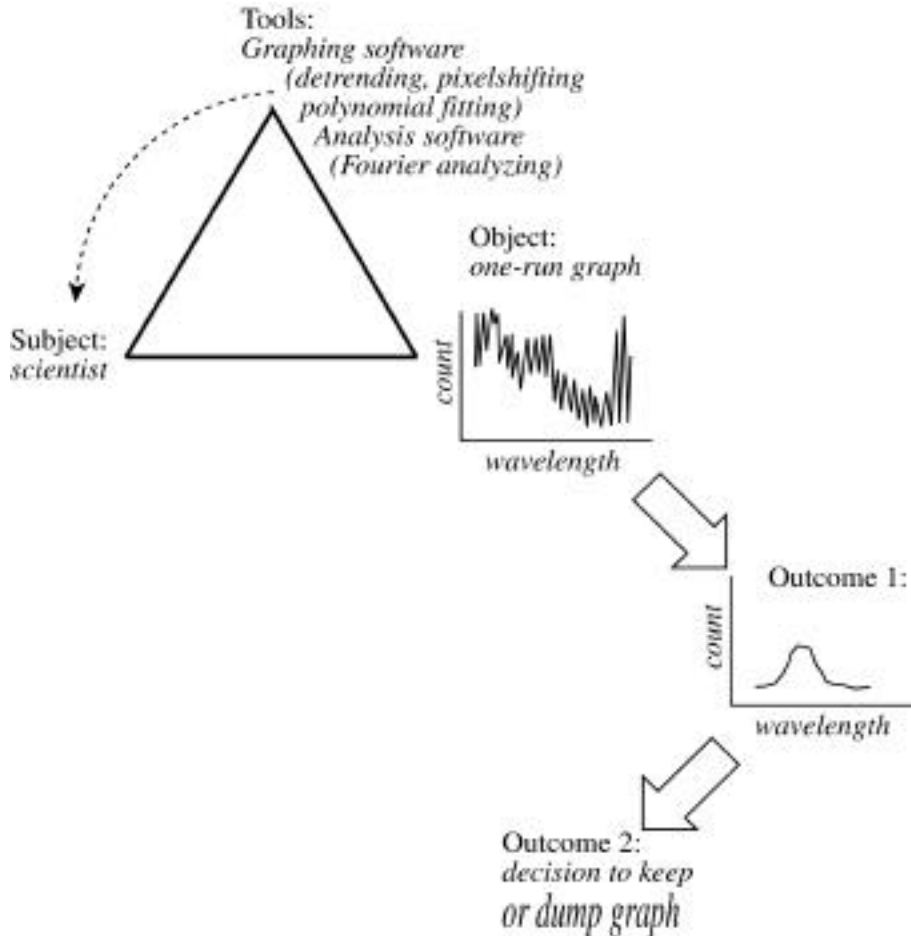


Figure 14. As scientists become familiar with tools and their effect on the objects (graph), they no longer need the tools in order to make decisions. They can perceive the final outcome through the clutter of the noisy raw graph.

Over time, the scientists come to make such decisions without first producing a transformed graph. That is, the tools and the effect that they have on the graphs appear to become transparent to the activity of reading. It is as if the scientists could see, by looking at the displayed graph, the result of the transformations that they had previously performed in a concrete way. An action, previously performed using a specific tool, has turned into an operation that is performed without requiring conscious attention.

In terms of the activity system depicted in Figure 14, we can think of the process requiring the tool as having been internalized leading to a change in the decision-making process about the future of a data run. This change is a change in the identity of the

person and a resultant, historical change in the activity system. Learning can be understood as the changing participation in ever-changing activity systems (Lave, 1993). Changing participation, however, makes learning visible and analyzable. In the present study, the slow disappearance of the tools that mediated graph interpretation and the seemingly unproblematic graph interpretation in real time suggest processes that activity theorists described as a change from overt actions to (internalized) operations (Holzkamp, 1983; Leont'ev, 1978). This internalization of previously external objects and processes is a change in the identity of the subject (Engeström, 1996; Lave, 1993).

INTERPRETATIONAL TRAJECTORIES

Traditional research on graphing was based on the assumption that there existed an isomorphism between mathematical representations such as graphs and the natural objects they have come to stand for (Lynch, 1991). As a consequence, graphical competence was to describe the ability to make inferences about the world when given a graph. Previous research has led us to suggest that the process is much more complex. Observations of scientists in the course of reading and interpreting graphs showed that they used existing, complex knowledge of the natural world as a resource for making sense of the graph (Roth & Bowen, 1999a). That is, we described graph interpretation as a dialectical process in which graphical analysis and analysis of natural situations that might have given rise to the graphs are mutually constitutive. When scientists were very familiar with a type of graph, such as when they talked about their own graph, graphs and the natural phenomena they stood for had become fused; the graphs appeared to have become transparent and reading graphs leapt beyond to the objects that they are said to be about (Roth & Bowen, 2001). They no longer distinguished between talking about an

aspect of the graph or an aspect of the world. We hypothesized that scientists were deeply familiar with the process by means of which particular graphs and natural objects came to be linked. In a sense, the graphs had come to represent not only the phenomenon but, in a metonymic way, the entire process of its construction. In the present ethnographic study, we described and theorized the process by means of which scientists come to read graphs in transparent ways.

Scientists do not simply make inferences from graphs about phenomena. Rather, their viewing of graphs is mediated by previous understandings, other graphs, and modifications made by the computing tools at hand. This mediation often disappears and therefore becomes transparent to those who study graphing. However, in cutting-edge research, the effects of mediation can still be traced and documented. In our paper, we present an activity-theoretical analysis how previous results of graph reading become new tools for viewing subsequent readings—a movement from *outcome* to *tools* in Figure 1. In subsequent developments, these tools are incorporated into other tools or internalized by the scientists. Particular aspects of graphs, such as features characterized as noise, then become transparent to the scientific gaze. When cognitive analysis merely studies the accomplished form of graph reading, it is blind to and neglects the mediated nature of human activity.

In the early stages of the research, the scientists were frequently uncertain about whether a graph represented a fact or an artifact. At this stage, they frequently used a variety of transformational and representational tools to enhance a display and thereby bring forth particular graphical features. Over time, the scientists came to read the graphs directly, without requiring transformations and reference graphs to make decisions about

the usefulness of their data. That is, graph interpretation was not a stable process of induction, but a process that changed in the course of the inquiry. As scientists became more and more familiar with their experiment and the graphs it produced, they came to see graphs as evidence of facts or artifacts in seemingly unmediated ways. That is, these later stages of graph reading are the result of a historical development in the course of which tool-mediated action became internalized and a process at the level of (unconscious) operation.

Traditionally, the relationship between graphs and their corresponding natural objects is taken to be isomorphic. Here we showed that a lot of work goes into the construction of the relation between graphs (signal) and natural object and between noise and its sources. This work is not unidirectional from natural objects to graphs. Rather, the work establishes graph and natural object at the same time as the outcome of a dialectical process. The graph is evidence for the presence of the phenomenon but the phenomenon exists only because of the graph. As a result of this process, graphs and their corresponding natural objects come to be fused so that talking about one is equivalent to talking about the other. Scientists point to a graphical peak and utter “this is a blue cone” or, viewing through the microscope, they might utter “this is a textbook example” which is equivalent to saying that the representation will have near publishable quality. Because of their familiarity with the process of constructing the link, scientists can easily “de-fuse” graphical representation and natural object, that is, make each an object of inquiry in its own right. If there is unexpected “ringing” or other forms of “noise,” the scientists backtrack through the set up to find its source. If the visual inspection of photoreceptors

under the microscope reveals trouble, scientists backtrack the steps by means of which the cells have been prepared.

In laboratory situations, graph reading differs significantly from situations where scientists are asked to read graphs with which they are unfamiliar though they are from introductory university courses in their own domain (e.g., Roth, Bowen, & Masciotra, in press). (There, a contractual agreement exists between the participant scientist and the researcher so that the former will do something that they not normally do.) In the present situation, the graphs are part of an activity system in which the research group is the subject. Members of the group change and modify the object and they know a lot about the transformation of the natural phenomenon through their own manipulations and the particulars of the scientific instruments. That is, scientists read graphs not only knowing a lot about the phenomenon but also about all the transformations by means of which a signal is generated from the object. This, of course, is virtually never the case in the research on graphing, which ends up attributing interpretations that deviate from the researcher's own to cognitive deficiencies.

In summary, all evidence in this study points to graph reading as a historically constituted process rather than an inborn ability or special competencies related to interpretation and inference. We hypothesize that the constructive work that brings together graphs and their corresponding natural objects is usually forgotten, an amnesia of the origins of graphical interpretation and understanding.

GRAPHING IN SCHOOL SCIENCE

Previous research on graphing attempted to make inferences about potential mental models and deficiencies that underlie graphing competence. In contrast, we focused on

the ways in which the participant scientists made available to each other (and to the analyst) their understanding, knowing, and learning. Here, we reflect on possible implications if the proposed view of graphing as everyday activity was to be extended to school mathematics and science activities.

In many investigations on graphing, high school students are asked questions about graphs that they frequently have no ideas about how these came to being. Students have never had the opportunity to produce graphs of the speed of an object and relate it to its appearance in graphical form. They have little or no experience with how modifications in the object (speed) and characteristics (troubles, noise) of the recording mechanism change different aspects of the corresponding graph. Students also have little or no experience with how graphs change when plotting parameters are changed, with the transformation of data, or with the fitting of data. In the few reported cases where students do have extensive experience with the transformation of natural objects into graphical representations and with the natural objects themselves they also become quite competent in interpreting new graphs pertaining to the domain (Nemirovsky et al., 1998; Roth, 1996). This is no different from what can be observed by following scientists in their daily work. Their competence in reading a graph is related to their familiarity with the object, the transformation it undergoes during the experimental process, and with the particulars of the entire chain of translations that produce and change the data (Roth & Bowen, 1999b).

Based on our research among scientists, we therefore expect to observe graphing competence only under special circumstances, such as when students have had much experience in translating natural objects into graphs and vice versa. Thus, curricula that

allow students to understand the processes by means of which graphs come to stand for natural phenomena will facilitate the emergence of the phenomenon of fusion and graphical competence. This contention is supported by the results of a small number of studies where students spent substantial amounts of time in producing graphs and linking graphs to phenomena (Mokros & Tinker, 1987; Nemirovsky et al., 1998; Roth, 1993, 1996). In all of these situations, students also developed a detailed understanding of the domain. Thus, when they were asked to read graphs relating to the domain, students exhibited great competence in producing suitable interpretations. On the other hand, we expect the students to experience (considerable) problems when they are asked to interpret graphs from different domains, requiring different data acquisition and transformation processes. We expect students to show even more trouble when they are unfamiliar with both data acquisition and natural phenomena. Thus, based on our work among scientists, we are not surprised that many students did not appropriately interpret graphs displaying oxygen levels and shrimp frequency as a function of distance from a factory (Preece & Janvier, 1992).

This study showed how scientists come to read graph in transparent ways. With respect to student cognition of graphing, much research remains to be done to document the trajectories students take when allowed extensive experiences of collecting data, transforming data, and displaying results of inquiries in graphical form.

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