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When Are Graphs Worth Ten Thousand Words? An Expert–Expert Study

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This study analyzes the interpretive activities of scientists related to familiar and unfamiliar graphs. The analyses show that when scientists were familiar with a graph, they read it transparently and thereby leapt beyond the material basis to the thing the graph is said to be about. In contrast, when scientists were less familiar with the particular graphs, their reading turned out to be a complex iterative process. In this process, scientists linked graphs to possible worlds by means of complex inferences. They checked whether an expression referred to the actual properties of the worldly things the graphs are speaking of. They also checked graphical expressions themselves on the basis of certain circumstances. In a few instances, the scientists abandoned all attempts in interpreting the graphs and classified them as meaningless. Grounded in the data, a 2-stage model is proposed. This model accounts for different levels of reading graphs observed in this study.

Graphical representations are central to scientific practice. They are tools used for analyzing and understanding scientific phenomena (Larkin & Simon, 1987) and they are central to the rhetoric of scientific communication (Latour, 1987; Meira, 1995). Scientists and engineers become dependent on graphical representations such that in their absence they fail to accomplish tasks (Tabachneck-Schijf, Leo-

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nardo, & Simon, 1997), interrupt meetings to fetch some representation (Henderson, 1991), or at least use gestures to reproduce transient facsimile in the air (Knorr-Cetina & Amann, 1990). It is virtually impossible to find a science textbook or scientific journal without graphs and diagrams. A recent survey of more than 2,500 pages from ecology research journals showed that there are 14 graphical representations per 10 journal pages (Roth, Bowen, & McGinn, 1999). A similar survey of chapters and journal articles from physics reported about 11 representations per 10 pages (Lemke, 1998). Finally, a survey of high school biology textbooks revealed the same frequency of representations, although the relative frequencies were different than those in the professional literature. Graphs predominate among the graphical representations (Roth et al., 1999). Despite this preponderance of graphs in scientific practice and science education, there is little work on the actual use of graphs in everyday science, or on scientists' reading of unfamiliar graphs. However, scientists are often upheld as experts when it comes to comparing their graph-related competencies to those of novices.

Our research program is concerned with the nature and level of expertise in graphing as these arise from the experiences individuals have at school, in the university, and on the job. This study was conducted to better understand graphing expertise. Therefore, we asked scientists to tell us what three chosen graphs refer to and mean to them. We were particularly interested in understanding the contributions of experience (content represented, laboratory experience, and understanding of conceptual frameworks) to the particular readings provided by scientists. Our empirical data show (a) that scientists cannot be taken as graphing experts in general and (b) that existing models of graphing expertise do not explain scientists' readings of unfamiliar graphs. We propose a two-stage model of reading graphs, which accounts both for interpreting processes and the perceptual structuring that yields the signifying elements prerequisite to interpretation.

BACKGROUND

The power of graphs comes from the topological character of the lines that articulate relations between the variables indicated on the axes (Roth & McGinn, 1998). The lines encode continuous change and are therefore suited to represent the dynamic nature of physical phenomena. Linguistic representations, on the other hand, divide the world into objects and classes of objects: Verbal representation is typological in character (Bastide, 1990). Graphs, consisting of combinations of topological and typological features, have specificity (what they cannot leave unsaid about the observed situation) that aids in their use for constructing logical arguments (Larkin & Simon, 1987; Stenning & Oberlander, 1995).

Graphs draw their power from two additional features. First, graphs are usually inseparably tied to mathematics. Mathematics bridges typological (verbal) and topological (graphical) representations and, although it has its origin in natural language, has substituted natural language particularly in those areas where it has proved to be semantically weak for representing material processes (Lemke, 1998). Therefore, the link between velocity–time and position–time graphs is provided by means of (a) the definition of velocity (v) as the first time derivative of the position (x), $x' = v = \frac{dx}{dt}$; and (b) the fact that in position–time graphs of x(t), the derivative $x'(t)$ is coextensive with the definition of velocity. Second, the variables that span the conceptual space in and of the representation are themselves results of typological processes that carve the world into discrete dimensions. For example, the labels *position* and *velocity* make salient particular aspects against all other aspects that conceivably describe the phenomenon of interest; this figure–ground distinction is a categorical one.

Past research often attributed differences between actual and expert performance to cognitive deficits (e.g., Berg & Smith, 1994) or misconceptions (e.g., Leinhardt, Zaslavsky, & Stein, 1990). There is a considerable body of literature on reading graphs suggesting that students confuse height and slope (e.g., Clement, 1989; McDermott, 1984). This literature was less concerned with ascertaining the degrees to which participants were familiar with the representations of, for example, the concepts of velocity and position and their relation. There is considerable evidence from the ethnomathematical literature that shows how tasks change when researchers change the way in which it is presented (Saxe, 1991). For example, whereas shoppers solve best-buy problems almost perfectly while walking through the aisles of the supermarket or simulation problems in front of the supermarket (95% accuracy), their performance drops to about 70% on structurally equivalent paper-and-pencil problems (Lave, 1988). That is, the representation of problems in the language and symbols of school mathematics lead to considerably lower performance levels.

The literature on ethnomathematics has alerted researchers to study the mathematics people actually do rather than what they do not do. Conventional approaches to mathematical representations are greatly enhanced by considerations of semiotic aspects of cognition (Becker, 1989; Becker & Varelas, 1993). In this study, we follow these directions and propose a semiotic framework that takes graphs as multimodal texts that are configured from a number of signs including topological (graphical, pictorial) and typological (mathematical, linguistic) elements.[1] In this framework, signs do not exist in a unitary way: Even relatively simple graphs lend themselves to be perceptually structured in different ways.

[1]Consistent with the semiotics literature (e.g., Eco, 1984), we use the word "sign" to denote entities that stand for or represent other entities. In the literature on mathematical cognition and mathematics education literature, the word "symbol" is often used in the same way (e.g., Kaput, 1987).

Semiotics is concerned both with understanding the relation of signs (or sign complexes) and their referents and with sign use (Eco, 1984). At the most basic level a sign consists of a portion of the material continuum, which serves as the sign vehicle. The sign is used to stand for the referent, also called the content of the sign, which itself is made up of portions of the material continuum. Therefore, the printed or uttered word "elk," both hands at the temples index fingers pointing up, or hoofprints all may be taken as signs that refer to something else: the sign referent or content of the sign. All three examples may in fact refer, although in different ways, to the same entity. Elk names a category of animals, the hands with index fingers up iconically represent the antlers of an elk (in a metonymic way they also denote an elk), and the hoofprints are indexical representations that allow us to infer the earlier presence of an elk. In (Peircean) semiotics, the relation between sign and referent can never be direct but is always mediated by other, interpretant signs.[2] In this article, interpretant signs are what our research participants (verbally, pictorially) produce when they are asked to explain what a graph means or refers to.

RESEARCH DESIGN

Our research program is concerned with understanding graphing and graph use from middle school to professional practice. In this study, we provide an analysis of graph interpretations by scientists, whom we had asked to serve as an expert reference group for other studies on graph-related cognition. Here, we are concerned with these experts' responses to a series of set tasks in an interview condition and their explanations of a graph of their own selection, usually culled from their everyday workplace.

Participants

The participants for this study were 16 practicing scientists. The scientists (S01–S16) were recruited at three universities and several federal and provincial government research branches. There were 15 men and 1 woman of Caucasian descent. Seven had obtained an MSc (3 were public sector scientists), and 9 had a PhD (5 public sector scientists); among the former, 3 were currently working on their PhD degrees. All participants had 5 or more years of experience conducting research for the purposes of publishing the results in reports and scientific presentations. All but 3 scientists (2 physicists, 1 forest engineer) can be classified as ecologists. Four scientists were tenured professors, 3 of these in biology departments, regularly engaging

[2]In contrast to Peircean semiotics, Saussurean semiology has only two terms and distinguishes between signifier and signified, corresponding to sign and referent in Peircean semiotics (e.g., Nöth, 1990).

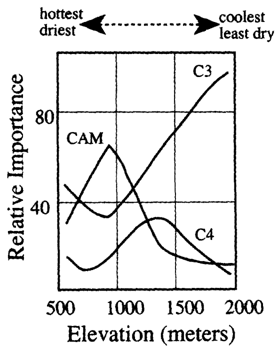
in the teaching of graduate and undergraduate classes in ecology and related fields. Four additional scientists were at the doctoral and postdoctoral level and engaged in regular university teaching or served as teaching assistants. All scientists have been highly successful in the past, some having received doctoral and postdoctoral awards, were recipients of national and international awards for their publications, and had sizable research projects in terms of the funding attracted from private and public sources. They had published regularly, an average of about two refereed publications per year (fewer for 2 of the 3 PhD students), with some individuals publishing as many as four and nine articles in a single year.

Task Design

In this study, we selected three graphs (typical in undergraduate textbooks) including a distribution, population (model), and isocline graph (Figure 1). A fourth graph was from the experts' own work, which they normally selected from a publication after being invited to participate in an interview by the researchers.

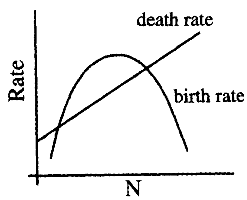
An analysis of ecology journals showed that the three graphs are common to the literature in ecology and in textbooks on the topic (Roth et al., 1999). One of the standard textbooks on ecology, for example, features 41 distributions, 19 graphical models with functional dependencies, and 65 isographs over a total of about 800 pages (Ricklefs, 1990). The three selected graphs differ in type and complexity. Figure 1a represents the relative frequency of occurrence of three plant types according to published data. The population dynamics graph (Figure 1b) represents a model that plots the functional relation of birthrate and death rate on population size, which itself depends on the rates. The isocline graphs (Figure 1c) represent three models of pairs of resources that affect some third variable, growth; the magnitude of the third variable is not directly available (as in a 3-D graph), but is depicted in the form of isoclines (lines of equal effect).

Distribution graph. The distribution graph (Figure 1a) is similar to that originally published in a scientific article that used it as data that confirmed a model according to which different metabolic pathways (i.e., C3, C4, CAM) afforded differential adaptation to the microclimate. The distinction between C3, C4, and CAM plants is part of the fundamentals of biology, usually taught during the first or second year at the university (e.g., Purves, Sadava, Orians, & Heller, 2001). The C3 and C4 designations directly relate to the number of carbons in the fixation of carbon dioxide. C3 plants make a three-carbon compound as the first stable product of carbon fixation. These plants lose up to 50% of their recently fixed carbon through photorespiration. C4 plants make a four-carbon compound that is subsequently transferred to specialized cells where carbon dioxide is internally released and refixed using the same compound that begins the C3 cycle. This process reduces carbon loss by photorespiration and in many cases completely inhibits it. CAM stands for Crassulacean acid metabolism, after the plants that use this a.



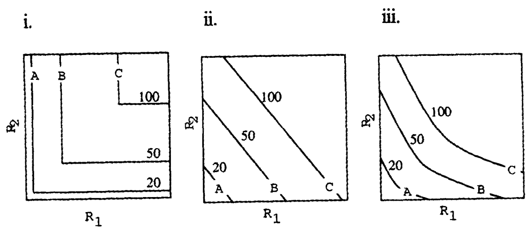
Distribution of C3, C4 and CAM (succulent) plants in the desert and semi-desert vegetation of Big Bend National Park, Texas, along a moisture and temperature gradient due to differences in elevation. CAM plants with nocturnal gas exchange for water conservation predominate in the hottest, driest environment, C4 plants are maximally important under intermediate temperature and moisture conditions, and C3 plants predominate at the cooler, least dry end of the gradient. (After data of W. B. Eickmeier [1978], *Photosynthetica, 12,* 290–297). What implications can you draw from this graph?

b.



In the derivation of the logistic model, we assume that, as N increased, birth rates declined linearly and death rates increased linearly. Now, let's assume that the birth rates follow a quadratic function (e.g., $b = B_0 + (k_b)N - (k_c)N^2$), such that the birth and death rates look like the figure. Such a function is biologically realistic if, for example, individuals have trouble finding mates when they are at very low density. Discuss the implication of the birth and death rates in the figure, as regards conservation of such a species. Focus on the birth and death rates at the two intersection points of the lines, and on what happens to population sizes in the zones of population size below, between, and above the intersection points.

c.



The amount a plant grows depends on a number of factors, for instance, the availability of nutrients (R). A shortage of any single nutrient can limit plant growth. Sometimes scientists study the effect of pairs of nutrients. The graphs depict three different biologically realistic scenarios of how two nutrients (R_1 and R_2) might combine to affect plant growth. Discuss the effects of different levels of the two nutrients on each amount of plant growth (20, 50, 100) in each scenario (i, ii, iii).

FIGURE 1 Three tasks were used in this research. These types of graphs are standard in introductory ecology courses and appear with considerable frequency in introductory ecology textbooks.

photosynthetic pathway. These plants close their stomata during the day to reduce water loss and open them at night for carbon uptake. Carbon is fixed into a four-carbon compound that is accumulated during the night. During the day, this compound internally releases carbon dioxide, which is then refixed using the same compound that starts the C3 mechanism. The CAM cycle effectively inhibits carbon loss by photorespiration.

The graph portrays the relative distribution of these three different kinds of plants along an elevation gradient, the data being recorded in Big Bend National Park, Texas. This elevation gradient was also associated with a temperature and moisture gradient. CAM and C3 distributions were on the same scale adding to 100%; the C4 distribution used a different scale in the original research. Our graph was modeled on that used in the lecture and in textbooks, and constituted a simplified equivalent of the original (some scatter removed, axes labels changed). We maintained the caption but formulated the task such that the participants were instructed to talk about the inferences that could be drawn from the graph. Therefore, this task closely resembled the activity of a person opening a journal and trying to make inferences without referring to the main text. To interpret the graph correctly, the relative positions of the three distributions along the elevation or climate variables have to be compared and attributed to the three photosynthetic metabolic processes (C3, C4, and CAM). The correct inference attributes the distributional differences to differential, climate-related (moisture, temperature) adaptation.

Population graph. Figure 1b constitutes the model of a density-dependent population in which the two lines represent birthrate and death rate; the caption specifies the respective functions as being quadratic and linear. Therefore, the task consists of establishing the dynamics of a population from the circular relations between population size (N = N[b,d] and the two rates b = b[N], d = d[N]). In this task, participants were specifically asked to focus on the two intersections and the resulting three sections along the abscissa. The correct interpretation identifies the two intersections as an unstable and a stable equilibrium, respectively, and provides the appropriate population changes near these equilibrium points. That is, below the lower equilibrium point ($N < N_{eq,\,1}$), the population crashes. Between the two equilibrium points, the population increases until it reaches the second equilibrium point, $N_{eq,\,2}$. Above the second equilibrium point ($N > N_{eq,\,2}$), the population decreases until it reaches $N_{eq,\,2}$.

Isocline graphs. Each of the three graphs in Figures 1c represents the conjoint effect of two variables on a third, where the third is represented by lines of equal effect. Graph i represents "essential resources," which can be mathematically represented as, for example (using convention of x representing horizontal, y the vertical axis, and z the axis coming out of the plane):

$$z(x, y) = \begin{Bmatrix} ax + b \text{ above line connecting vertices} \\ cy + d \text{ below line connecting vertices} \end{Bmatrix}$$

Graph ii represents "substitutable resources" that can be represented mathematically as $z(x, y) = ax + by + c$. Therefore, the two resources are substitutable in the proportion of a and b. Simply saying that the model is linear does not distinguish it from the first graph, which is also linear in one or the other variable. Finally, the third graph (Figure 1ciii) represents "complementary resources" because there is some optimum combination that minimizes the sum of the individual components. Mathematically, the equation, $z(x, y) = (a \cdot x + b) \cdot (c \cdot y + d)$, yields isoclines in the way presented.

A correct interpretation of Graph i points out that the effect of the resources (independent variables) on the dependent variable is given (limited) by their values at the elbow. For any given value of one resource, the level of the dependent variable is fixed and does not change with the amount of the second resource. In other words, to obtain a certain level of the dependent variable, both resources have to be above some minimum (essential) level. A correct interpretation of the second graph articulates the additive effect. Lower values in one resource can be compensated with proportionally higher values in the other variable to maintain a constant effect; that is, one resource can be substituted by a proportionally constant amount of the other. A correct interpretation of Graph iii brings out the interactional nature of the two resources, with some minimum total amount achieved by the complementary nature of the two resources.

Graphs from scientists' own work. Scientists normally prepared entire research articles or reports or, alternatively, printouts of individual graphs they had previously published. Most graphs were Cartesian, including many lines that portrayed the relation between two variables or the interaction of two independent variables on a third variable. In some instances, variables were collapsed into categories. In one instance, this was used to allow data analysis via an analysis of variance. In another instance, the interaction of two variables on a third could be represented in the form of a table rather than requiring the representation of a surface in a 3-D diagram. In a third case, the dependent variable was coded 1 (*presence of organism*) and 0 (*absence of organism*) and represented as a function of two independent variables.

Procedure

The interviews were conducted to accommodate the scientists. Eight individuals chose to do the sessions in their own offices; the others were recorded in the principal investigator's office or laboratory. The graphs were presented in the order that they appear in the previous section: distribution graph, population graph, resources graph, and own graph.

For each graph, scientists were asked to tell us as much as they could about the graph, drawing on all information given including the captions. They were asked to read aloud, when they were reading, and to describe what they were seeing when they looked at a graph. When the participants stopped talking for more than a few seconds, the investigator encouraged them to further verbal productions by inviting them to "say what you are thinking right now." They were instructed to indicate when they considered themselves to be done and had nothing more to say. In this case, the investigator presented the next graph. At the end of the third graph, the investigator invited the participant to present his or her own graph; if there were several, the participant was asked to pick any one. They were asked to provide a reading of the graph, assuming that the investigator was not a specialist in the field.

The sessions lasted between 1 and 2 hr. The sessions were transcribed, including the gestures used by scientists to point to some feature or to represent some aspect of the graph in iconic fashion. The total word production across the four tasks ranged from a low of 5,400 words to a high of 10,000 words.

Data Analysis

Over the past 9 years, we developed a successful methodology for analyzing graphs, graphing, and graph use from an anthropological perspective (Roth, 1996, 2003; Roth et al., 1999) through successive methodological refinements culminating in the work presented here. Our analyses are based on the assumption that reasoning is observable in the form of socially structured and embodied activity (Garfinkel, 1991). In our analyses, videotapes, transcripts, and artifacts produced by the observed individuals are natural protocols of their efforts in making sense of, and imposing structure on, their activities. These protocols constituted our texts, which we then elaborated in analyses.

We independently read all transcripts and viewed all videotaped interviews before meeting for collaborative analysis. We conducted extensive collaborative analyses of 3 of the 16 interviews; during these collaborative analyses we ascertained that we in fact coded the transcripts in the same way, which was facilitated by the fact that we had already collaboratively conducted research on graphing since 1992. This long-term collaboration turned out to be an advantage, for groups that work together for a long time achieve strong agreement and high interrater reliability (Schoenfeld, 1992). Because we were interested in classifying all cases, we negotiated until agreement was reached. Videotape replay was stopped whenever one of us thought a significant event had occurred. This person then stated an assertion before the event was reviewed as often as necessary for a full exploration by both researchers. For example, an early record in our analysis contained the first two diagrams and the codes "doesn't make sense" (S01, S03, S08), which led to the hypothesis, "experts use topological features to decide if a graph is reasonable" (see following section, "Lacking

(Realistic) Referent"). The code "tracking across" together with scientists' tracking of features exemplified in the third graph led us to hypothesize, "What aspect is salient and how saliency is described affords valid interpretation." We then reviewed other episodes to check the degree to which they confirmed or disconfirmed the assertion. On the basis of these checks, we reformulated initial assertions until they were representative of the data. We discussed personal constructions, subjected them to critique and analysis, and tested them in the entire data set to evaluate fit and plausibility. From the assertions, we then built our model (see the following).

Both authors had been trained as natural scientists (Roth, MSc in physics, applied mathematics; Bowen, MSc in marine ecology), which entails the possibility that we may have "gone native," a situation often discussed as a danger in the literature on ethnography as method: "'Going native' is said to mean the end of scientific knowledge" (Rosaldo, 1989, p.180). As natives, we may have overlooked important tacit aspects of scientific practice and fallen into the trap of applying concepts without appropriately analyzing them. To deal with this possibility, anthropologists recommend using techniques that disrupt common sense (Marcus & Fischer, 1986). To deal with the possibility that our scientific common sense limited our analysis, we deliberately produced alternate readings of the data that we subsequently analyzed in terms of the assumptions they make. The ecologist (Bowen) read the transcripts in the light of his own learning process related to graphing during his undergraduate and graduate training; the other (Roth) engaged in structural (mathematical) analyses (e.g., task analysis). These distinctly different readings provided different inroads to the cognitive difficulties of graphical representations during lectures. By engaging alternate forms of reading, we attempted to circumvent "a reduction of understanding to empathy and a reduction of explanation to an abstract combinatory system" (Ricœur, 1991, p. 19).

TWO-STAGE MODEL OF GRAPH INTERPRETATION

As a result of this study, we developed a model that accounts for the different aspects of the graph interpretations in our database. We first present this model and provide detailed examples from our database in the subsequent section. The development of our model was driven by, among other influences, two important observations not presented or accounted for in other expert studies. First, previous studies assumed that the ontology of the domain within which the experts reasoned was given and constant. In other words, it was assumed that certain features, such as the intersection of two curves, were elements that the expert would necessarily and *naturally* attend to (e.g., Pinker, 1990; Tabachneck-Schijf et al., 1997). Our data do not support this assumption but suggest that this is a special case that occurs when experts are highly familiar with a particular graph. Second, interpretation is taken to be an inferential process by means of which experts move from a given sign (graphical feature, word, or text) to its content (e.g., Wineburg, 1998). Our previous work had already revealed that interpretation is a reflexive and constitutive process in which particular readings of signs and potential content are mutually adjusted until they are consistent (Roth & Bowen, 1999). In some situations, when such an adjustment of sign and referent is not possible, experts question the sign itself and begin to question whether they are "looking in the right way" at a graph and the text that accompanies it. On the other hand, if an expert is very familiar with a graph, we no longer speak of inference but of transparent reading because the conflation (fusion) of sign and referent makes inferential processes unnecessary. Here, we first present the model and then provide detailed data justifying the choice of our model in subsequent sections.

Interpretive Process

There are two component processes in our model, structuring and interpreting. We understand the interpretive process like this. Once an expert has isolated a feature, such as the intersection of the birthrate and death rate curves (Figure 1b), it can become the sign for something other than itself, its referent, which is the content of the sign. For example, the referent of the intersection might be "equilibrium." However, an intersection in itself does not refer to an equilibrium state; rather, the nature of the referent depends on the contextual constituents of the sign and on the community-specific rules that control sign-referent relations.[3] Each verbal or graphical production by an expert therefore pertained to establishing a four-parameter relation linking the content (referent) on the one hand with sign in its context given the rules that the embedding scientific community of practice imposes on such relations (Barwise, 1988). Rather than arriving at the isomorphism world $\leftrightarrow$ mathematical form that expresses the classical view of scientific measurement (Lynch, 1992), we arrive at the relation

$$\text{content} \underset{\text{rules}}{\leftrightarrow} \text{sign (context)} \tag{1}$$

where content normally is some aspect of a natural phenomenon. Relation 1 articulates a correspondence or mapping between material segmentations (that serve as signs and natural) from dissimilar domains (Eco, 1984), natural phenomena on the one hand and graphical features and words on the other. The nature of the sign depends on the context. Finally, because the relation is mediated by community-specific rules, it does not normally express an isomorphism. Unless the rules of the mapping are explicitly available in a graphical representation, it is difficult to impossible to reconstruct the relation between the graph and its content.

We take the result of an interpretive process, the "interpretation," to consist of a set {content, sign, context, rules} that the interpreting expert takes as satisfying Relation 1. In the interpretive process itself, the expert seeks to generate suitable values

[3]Eco (1984) noted that even the relation between iconic representations, such as naturalistic drawings and pictograms, and their referents has to be learned and is not a natural kind.

that satisfy the relation. Often, some values of context and rules are implicit or taken for granted so that they do not have to be evoked in words or graphically ("they go without saying"). Two remarks are useful here. First, there are many, potentially infinite sets of {content, sign, context, rules} that may fit the relation. The pertinent literature refers to this open nature of the interpretive process as unlimited semiosis (Eco, 1984). Second, in working toward finding a set {content, sign, context, rules}, alternative approaches are available to experts. They might begin with a particular referent situation and then find how it would be expressed in a chosen sign system so that the relation is satisfied given the rules of their community of practice; or, they might begin by fixing a particular sign and then make inferences about possible referents that satisfy the four-parameter relation. They might move back and forth between the two approaches, which we described in our earlier research as a mutually constitutive process that stabilizes sign and referent (Roth & Bowen, 1999).

Of particular importance to the way in which signs are interpreted are contextual constituents. Articulated and nonarticulated (non-) constituents and conventional rules modulate each sign (Barwise, 1989). For example, in the context of the population graph (Figure 1b), the signs /birthrate/ and /death rate/ are articulated constituents of the respective lines.[4] Each articulated constituent assists the reader to establish referents that are external to the graph. Articulated constituents may be along a gradient from general to specific. The sign /Variable 1/ in Figure 1ciii would be a very general articulated constituent; /R1/ or /Resource 1/ is already more specific, particularly in the context set up by the caption; finally, /nitrogen/ or /potassium phosphate/ would be very specific constituents of the graph. Unarticulated constituents (as unarticulated conventions for use of axes) are aspects of the graph that are constitutive of its content, but not made explicit in the representation or in the interpretation. For example, the fact that the abscissa values increase from left to right, and the ordinate values from bottom to top, is central to the accepted content of the graph but is not available. Also unavailable is the fact that death rate contributes in a negative way to the current population size, although its slope has a positive value in this graph. In banking, for example, and embodied in spreadsheets, losses are "signed" negative; thus, total movement of accounts are evaluated by adding losses and gains; here, death rate has to be subtracted from birthrate to evaluate the net rate of change on the population size. The sign /N/ is frequently taken as standing for something like "number of individuals" or "population density," although our scientists often did not use the interpretants /number of individuals/ or /population density/.[5] Although not available in the graph itself, the content of /N/ may be inferred from a sentence in

[4]We use a slash before and after a word (e.g., /Resource 1/) to indicate that it is a sign in our model.

[5]Barwise (1989) also deals with articulated nonconstituents (e.g., existing grid lines do not constitute the meaning of the graph) and unarticulated nonconstituents (e.g., orthogonal projections of each curve point onto axes that attribute specific values to the point).

the caption, "Such a function is biologically realistic if, for example, individuals have trouble finding mates when they are at very low density" (Figure 1b).

Structuring Processes

Most cognitive research assumes that graphs contain readily identifiable features that the expert takes as signs for something else. For example, Pinker (1990) noted that in experts "the visual system *naturally* encodes the geometric features of the graph" (p. 121, emphasis added). In a similar way, Tabachneck-Schijf et al.'s (1997) CaMeRa system also works on the basis of the (automatic) encoding of the visual field. However, our data show that geometric features are not inherently salient or are not salient to the experts unless they are already very familiar with the type of graphs. There are moments when the experts engage in perceptual work to structure the graph and associated text and thereby isolate features that can serve as signs. As the experts scan a given graph and text, there are experience-based gestalts that give rise to perceptually salient features. These features become the signs and contextual constituents for the interpretive process. When experts could not make sense of a sign (i.e., when they could not find a solution to the four-parameter Relation 1), they began to search for alternate features that could serve as signs. This search for alternate features was indicated, for example, by productions such as "I have to look at this in a different way."

Conditions for Correct Interpretations

Arriving at the correct interpretation requires that experts identify all elements in the set {content, sign, context, rules} and relate them in an appropriate way. Interpretation then becomes a problem of satisfying a series of mutually constraining influences of individual signs within a matrix of signs. In this study, nonstandard interpretations were sometimes attributable to different structuring leading to different signs or to failure in using particular features as contextual constituents to constrain the sign in question (i.e., the graphical display itself did not tell these scientists how to read the graph but rather always lent itself to multiple interpretations). Some philosophers insist that the possibility for multiple interpretations is inherent in the nature of a sign (Derrida, 1988). Seen from this perspective, alternative and nonstandard interpretations do not come as a surprise. For example, in the context of the population dynamics graph, the most common alternative interpretation was based on not perceiving the functional dependency of birthrate and death rate on the population density. Therefore, some scientists read /b – d < 0/ on the right end of the graph as /population crashes/. They did not see that in this situation, one of the constituents of /b – d/ is /N/, which marks the abscissa. Therefore, these scientists did not contextualize their reading of /d[N] – b[N]/ in terms of /N/; the sign /d[N] – b[N]/ was read independent of the constituent /N/. Therefore, they concluded that /d – b < 0/ denoted population crash rather than "population decrease."

RESULTS

This study was designed to provide a better understanding of how scientists interpret unfamiliar graphs. We focus on the interpretations of graphs by scientist experts in a controlled situation rather than in their graph-related cognition at work, which, for a variety of contextual factors, changes their performance (e.g., Roth, in 2003). They were generally much less familiar with the graphing tasks that were presented to them than with their own graphs. We observed great variation in the interpretations by the experts, which our model predicts to be the result of different solutions to the four-parameter set {content, sign, context, rules} that enter into the relation expressed in (Relation 1). In this study, we are principally concerned with differences in signifying features, contextual constituents, and referent/content domains. After presenting the levels of correct interpretations (section entitled, "Levels of Performance"), we articulate sources for difference and incorrect interpretations in the following sections: "Differences in Contextual Constituents and Salient Features," "Differences in Referents," and "Dialectic and Iteration." Our final section, "Familiar Graphs: Transparent Reading," provides an overview of the different performances when scientists talked about the meaning of graphs from their own work, principally related to their intimate knowledge of the content domain.

LEVELS OF PERFORMANCE

In the case of the distribution graph (Figure 1a), nine (56%) of the scientists causally linked the different positions of the distributions along the elevation gradient to the different photosynthetic mechanisms (C3, C4, CAM) or explicitly specified differential adaptation as the cause for the data as represented (Table 1). The scientists did somewhat better on identifying the intersections on the population graphs (Figure 1b) as stable equilibrium (n = 12, 75%) and unstable equilibrium (n = 10, 63%); only one scientist (6%) identified the largest increase of the population size where the function $(b[N] - d[N]) \cdot N$ was maximized; all others, in about equal numbers, suggested those abscissa values where $b = b_{max}$ and $(b - d) = (b - d)_{max}$. Finally, one half of the scientists (n = 50%) provided readings of the isoclines (Figure 1c) that were consistent with the concepts of "essential," "substitutable," and "complementary resources." Using the number of correct interpretations as criterion variables (Table 1), scientists who are based at the university or college level tended to be more successful than their nonteaching colleagues, $t(14) = 3.88$, $p = .002$. Clearly, the university-based scientists, involved in teaching or serving as teaching assistants, were more familiar with doing such interpretive tasks (because they teach their students to do them) or with the materials than the nonuniversity public sector scientists. Because the number of scientists with master's degrees was nearly evenly spread across the two groups, the differences between the two groups cannot be attributed to differential training in graphing practices.

TABLE 1
Frequency of Standard Answers

	Frequency (Count)		
Task	*University (N = 8)*	*Public Sector (N = 8)*	*Total (N = 16)*
Distribution			
Adaptation	7	2	9
Population graph			
Unstable equilibrium	8	4	12
Stable equilibrium	7	3	10
Largest increase in N	1	0	1
Isoclines			
Essentiality	6	2	8
Substitutability	6	2	8
Complementarity	6	2	8
Summary Statistics	$X = 5.13$	$X = 1.75$	
	$SD = 1.69$	$SD = 1.81$	

Initially surprising and contrary to the assumption that graphing is a core scientific skill, a considerable number of scientists expressed difficulties reading the distribution ($n = 5$), population ($n = 2$), and isocline graphs ($n = 8$). Therefore, with varying frequency, scientists suggested that a graph was "a challenge to interpret," "not something I am dealing with," "a bad graph," "Christ almighty, confusing," or "Why do people make graphs like this?" The comparison between these results and Table 1 suggests that there exists an inverse relation between the overall success rate on each task and the rate of specifications of difficulty. These findings are consistent with those of Wineburg (1998), who found that an expert less familiar with the domain uttered a significantly higher number of comments regarding his level of knowledge ("ignorance") than the expert who was intimately familiar with the topic.

DIFFERENCES IN CONTEXTUAL CONSTITUENTS AND SALIENT FEATURES

In our model, the contextual constituents and salient signifying features (i.e., signs) are important aspects of an interpretation (i.e., a set {content, sign, context, rules} that yields a satisfactory relation). There was considerable variation between and sometimes within scientists as to the particular constituents and salient features that entered their interpretative work, leading, not surprisingly, to differences in the interpretation.

Contextual Constituents for "Standard" Interpretations

Each graph (including the associated text) can be understood as an array of signs. To arrive at a normative, standard interpretation, the ensemble of signs and their relation have to be read in particular ways. However, we observed considerable variations in how individual signs were used, making the considerable variations in overall interpretation hardly surprising. For example, scientists constructed different referents for the sign /N/, the label on the abscissa of the population graph (Figure 1cii). Scientists noted that /N/ denoted "population (organisms, atoms) size" ($n=8$), "number of individuals" ($n=3$), or "population density" ($n=5$). Two individuals used N as an unspecified variable, and one scientist used it to denote time. Scientists sometimes suggested that the denotation "always" held. This use of always suggests a typical case of conventional constraint such that the content of /N/ is population density. These constraints are consistent across several scientific domains such that /N/ is used in the same way in physics, chemistry, or statistics. Other scientists did not use conventional constraint to establish how to use /N/; rather, other signs were used as constituents to arrive at population density as the referent of /N/. Therefore, /birthrate/, /b = $B_0 + k_b \cdot N + k_c \cdot N^2$/ and /such a function is reasonable at very low density/ are articulated constituents of /N/, which allowed participants to recover the appropriate referent population density even when the conventional use of /N/ was not salient at the moment. However, scientists did not use the words they identified (i.e., typological signs) to constrain their referents.

Salient Features

Correct interpretations assume that the experts perceptually isolate the appropriate sign. We already noted that scientists constructed different contextual constituents for the signs they isolated. Even more surprising to us was the fact that scientists differed in their isolation of features from a graph. We even observed within-scientist variations, which occurred when the initially isolated features did not lead to a result satisfying to the expert. For example, when S07 asked himself where the population would be constant, he began to focus (incorrectly so for arriving at a standard interpretation) on the point where the slopes of birthrate and death rate graphs were the same[6]:

> S07: Well, you know, you reach a point of course where the slopes are the same [Points to graphs where the slopes of birthrate and death rate are the same] you got sort of a constant, you know, birth and

[6]The following transcription conventions are used: (a) [Points to "N"]: Transcribers' comments, such as observable gestures or descriptions of entities referred to, appear in brackets; (b) °Population°: Degree signs enclose utterances spoken with a very low, almost inaudible, voice; (c) Down here-: The hyphen is used to denote a full, sudden stop in the utterance.

death rates, and population sizes maintain, I guess, whereas over here [Points to right-most side of graph] it's decreasing.

In this situation, S07 attempted to interpret the graph in terms of the relation between the slopes of birthrate and death rate graphs; he continued talking about the different parts of the graph in terms of the slopes. However, 2 min later he changed his focus, now comparing the values of the two graphs at a particular population size:

S07: Well, I mean, OK, down here, I mean, you've got birthrate at a certain level given a certain size of population and death rate is at a higher level in each, in each end. Given that this is certain population level at time whatever it is, you know, your population is decreasing. [Pause] I would think.

Such episodes show that the context of the scientist's current inquiry shaped which aspect of the graph would be salient.

Features of a graph are usually accepted as given a priori. Therefore, features such as intercepts, intersections, (relative) slopes, (relative) maxima, and (relative) minima are taken as a priori salient elements. However, our analysis of all transcripts shows that such features are not attended to by default; whether a feature is relevant appears to be a function of the type of graph and the phenomena displayed. There is a considerable variation within and across individuals for making salient and attending to possible referents of such features (Table 2). (During the analysis, all features made salient by the participants were noted and later compared, by type, across tasks and sessions.) For example, in the population graph task, all research participants attended to the intersections; this is not surprising given that the task explicitly asked them to "Focus on the birth and death rates at the intersection points." On the other hand, the intersections in the distribution graph task were addressed by none of the scientists. Finally, 11 of the scientists (69%) made explicit reference to the absence of intersections in the isocline graph.

In the same vein, a pertinent feature of the population dynamics graph, the maximum of the birthrate curve, /b_{max}/, was a salient sign in only two interpretations (S01, S02). On the other hand, all but one scientist (S15) pointed to either /b_{max}/ or

TABLE 2
Frequency (Counts) of Four Salient Features in Three Tasks

Graph type	*Feature Intercepts*	*Intersections*	*(Relative) Slope*	*(Relative) Minima, Maxima*
Distribution	0	0	0	8
Population	5	16	8	7
Isocline	1	11	4	—

/$(b - d)_{max}$/ when asked where they would expect the maximum number of individuals added to the population between 2 years:

> S08: You got some optimum population size then we're gonna get the maximum return [Points to b_{max}] and ... there is a trade off between death rates and birth rates but we're looking here at the point where you're getting the maximum number born [Points to b_{max}] to what, compared to the number that are being lost [Points to death rate at $N = N[b_{max}]$].

Here, the highest point of the birthrate curve and the greatest distance between birthrate and death rate stood out perceptually and led the experts to their answers. However, these differences became salient not as a matter of course but in the context of a question. Furthermore, both answers are inappropriate because the largest increase in individuals (over 1 year) is given by the maximum of the function $(b - d) \cdot N$, the answer suggested by S15:

> S15: Because the curves represent rates rather than actual numbers, the absolute numbers of dying and born animals will be b times N and d times N. So the change in actual animals in this case will be b minus d times N.

Therefore, the nature of salient geometric features in a graph cannot be taken as given but has to be established empirically, especially when graphs are unfamiliar.

It is evident that the nature of the response depends on which geometric features are salient and therefore become a signifying element /S/. For example, S04 tracked all three isographs at a constant value R_2 from left to right and then suggested that Figure 1ci referred to "absolute limits above which additional quantities in Resource 1 do not have any effects":

> S04: So, basically it says that [Figure 1ci], that, if you are anywhere in this region [Moves finger along horizontal of Line A, 20], that you have a growth rate of twenty. Which means that no matter how much R-one you have, if you have less than this much R-two, then you can't grow more than twenty.

Figure 1cii meant to him "two resources are perfectly substitutable." Finally, in Figure 1ciii, the resources denoted to him "partially substitutable resources," for it took much more of R_1 to substitute an equal amount of R_2. S16 tracked all three types of curves, each one along an entire isocline. He then suggested that the content of Figure 1ci was "essential resources." He reasoned, "You had to have a certain amount of R_1 and R_2, indicated by the values at the corners, for certain growth rates to occur." He further elaborated Figure 1cii in terms of /two resources of which one could substitute the other/; and in Figure 1ciii, he made salient the elbow where the total amount of $R_1 + R_2$ was a minimum suggesting that the curve represented "complementary resources."

Here, we have two different interpretations, both acceptable, but based on different geometric features (instantiated in gestures and pencil lines added), and making salient different concepts. In the first interpretation, amounts R_1 along some horizontal line (R_2 = constant) are salient as are the distances between adjacent curves. In the second interpretation, the amount of R_1 and R_2 at the elbows (i, iii), and the nonexistence of an elbow in case ii were salient and formed the basis of the interpretation. Furthermore, for the isocline graph there was no within-subjects and between-subject consistency across our two samples for focusing on elbows, shapes, or distance between curves. Some interpretations made salient the elbows in one curve, but the overall shape in a second curve; interpretations highlighted the corners in Figure 1ci, but centered on the location of the intercepts in Figures 1cii and 1ciii. The geometrically salient features of the isographs differed considerably between interpretations. Two scientists (S04, S06) perceived the isographs holistically, ordered the contours i, iii, ii (Figure 1c) and suggested that graph iii lay between the extremes i and ii.

DIFFERENCES IN REFERENTS

Our earlier work showed that scientists did not simply interpret graphs through an inferential process (Roth & Bowen, 1999). Rather, there was a dialectic movement whereby situations (referents) and graphs (signs) were mutually adjusted and thereby stabilized. In the model that we present here, scientist experts appear to try different values of content and sign until they find a suitable pair that, with appropriate context and rules, provides an intelligible interpretation. This study allowed us to arrive at a much more comprehensive model, whereby interpretation involves finding a solution to a four-parameter relation. During the sessions, we observed experts in the production statements in the course of finding possible solutions to the relation articulated in (Relation 1). Our model predicts that there are many possible solutions—depending on the nature of the parameters. Even if one or two of these parameters were taken as fixed, there would still remain considerable flexibility in suitable pairs of the remaining parameters. In other words, even if two experts were to isolate the same features (signs) of a graph (which is not always the case as we showed), differences in the referents that they consider would lead to different verbal and graphical productions and therefore interpretations. Therefore, they were solving a different problem, working on a solution to a different set of parameters in the set {content, sign, context, rules}.

The experts already differed on a surface level, in the concerns that they brought to the role of scientific knowledge. Therefore, the university-based scientists focused on the production of knowledge independent of potential uses; the public sector scientists (although they also produced scientific papers and journal articles) were more concerned with the practical use of knowledge for management purposes. Contrary to our initial expectations of a more uniform interpretation of graphs by scientific experts, there were considerable variations among scientists along the lines of referent domains (i.e., real or potential referents). Specifically, we distinguished four types of situations. Especially field ecologists often thought of ecological situations with which they were familiar, whereas theoretical ecologists and physicists talked about graphical or mathematical models. In some situations, scientists used vernacular, everyday examples or simple hypothetical situations. Finally, some scientists considered one or all graphs as meaningless (i.e., empty of content).

Ecological Situations

Field ecologists elaborated referents in terms of ecological situations with which they were familiar. That is, the referents—which, in turn, served as test cases for their understanding of the graph—came from their experience in actual field situations or from vicarious experiences familiar to them through the common practices and stories in their scholarly community. In these situations, the ecological phenomenon was the major concern shaping the reading of the graphs. In the following example, the expert attempted to get a handle on the population graph by talking about a specific situation, the crash of the Atlantic cod stocks around Newfoundland. He suggested that their recent history would require a multiple stable state model, inconsistent with this graph:

> S04: Cod is not a good example, because that actually requires more than just two species. It requires that the cod are at a point, what's known as a multiple stable state. What you want is a third equilibrium, which is in fact stable. And that requires something that looks like this [Draws Figure 2].

After having constructed the new graph in the context of Atlantic cod, this scientist then attempted to evaluate whether the model he had drawn was appropriate in other situations. Here, he talked about the moose–wolf interactions, which has been studied on Isle Royal for over 40 years and has become a paradigm case for the teaching of ecology. Based on his understanding, he attempted to reconstruct a new scenario in which each section of both graphs could be mapped onto the natural populations. This reconstruction occurred through a dialectic process between two poles. On the one hand was his understanding of the moose–wolf interaction. For example, he suggested that "wolves are territorial, leading to a decline in death rates at large moose populations" or that "moose birthrates are up at low N, be-

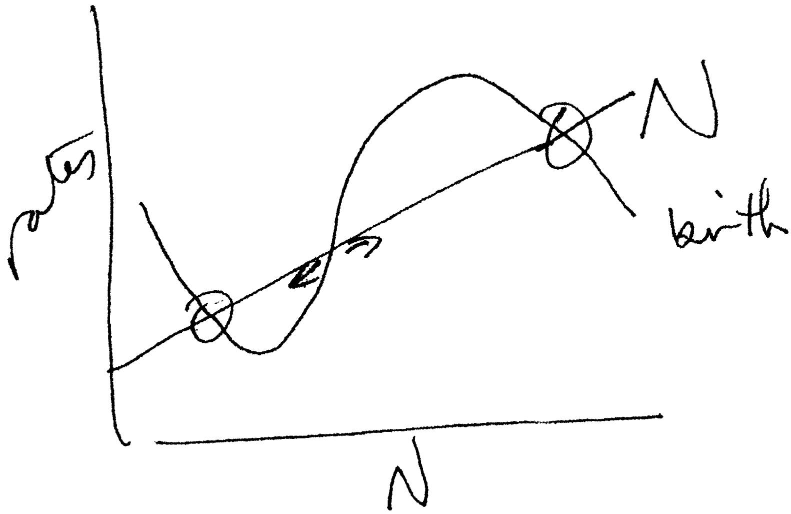


FIGURE 2 S04 constructs a graph that expresses his understanding of the historical events around the collapse of the Atlantic cod population off the coast of Newfoundland, which shifted from an equilibrium point at high numbers to a substantially lower equilibrium point. He then reified his graph by using it to discuss the relation between moose and wolf population in the Canadian arctic.

cause there is no wolf predation, for the population is too small to support any wolf population." On the other hand was the fact that he needed three intersections (2 stable equilibria and 1 unstable equilibrium). S04 never completed this second example because he could not immediately translate between the two. That is, the content and sign he had produced did not fit together into a coherent set. It may also have been that, at the moment, he did not distinguish between two types of population dynamics graphs, which make use of $\frac{dN}{dt}$ curves. (In the other type of graphical representation, the predator and prey isoclines for $\frac{dN_{\text{pred, prey}}}{dt} = 0$ are plotted rather than $\frac{dN_+}{dt}$ [birthrate] and $\frac{dN_-}{dt}$ [death rate] as in this example.)

In another example, after expert S12 developed a description of the elk population in Banff National Park (content), with which he was very familiar, he hypothesized a possible representation in graphical form (sign). That is, he began with the situation description (content) and then described his expectation about the graphical representation of one of its aspects (birthrate):

S12: If you're managing elk in Banff what kind of, what kind of things will happen if you maintain the population at different densities?

> So, will birthrate always go up as the population of elk goes up? And there will probably be some reasons for that not being true. That is, as the population gets close to its carrying capacity there should be some negative impact on the next individual that's born—limited resources, limited spaces, these types of things. They may not be able to find winter habitat and they may be vulnerable to predation. So, we imagine that birthrate is going to be, not be, not be increasing in a linear fashion.

Managing elk in Banff National Park is a well-known ecological problem in Canada, often featured on television in wintertime when the animals appear to take over the town. Every visitor to the area has seen large numbers of these animals, walking into town during the harsher winter months. From this ecologist's perspective, any additional animal to this already large population (which is possibly near the carrying capacity of the region) will experience a negative impact because of the shortage in different types of resources. Therefore, his intimate knowledge of the situation allowed him to construct a plausible argument for the birthrate curve not to be linear, and to drop off for larger populations. The birthrate is curvilinear (with a negative curvature), which points to decreasing birthrates, and the decreasing birthrates observable in situations such as the elk population make the graph a plausible model for the theoretical function displayed on the graph.

Finally, S02, who researched lizards in the mountains, invoked the changing climes and fauna that can be directly experienced on the West Coast, or on any trip into the Rocky Mountains, Alps, or other mountain ranges ("So the low elevation is the hottest, driest and the highest elevation the coolest, least dry. Hum. °Moisture and temperature° ah OK, so it- Just as you go up it gets colder and wetter, that makes sense"). She established that CAM plants have an advantage in hot dry climates because their photosynthetic mechanism allows them to conserve moisture ("these, I guess CAM are succulents so that's some kind of, I can't think of how these things are called, anyway they are obviously very good at holding on the moisture"). She had also established that C3 plants are better adapted to the higher levels with moister and cooler climates ("these guys [Points to C3] are probably adapted, what's 2000 meters, that's fairly high, so they're probably adapted so much to that higher elevation, certainly accustomed to a lot more moisture"). Given these premises, the relative success of C3 and C4 below 900 and 500 meters, respectively, compared to CAM plants did not make sense:

> S02: That seems weird to me, why there would be a dip [Points to C3 at 950 meters], and then the same down there [Points to C4 at 750 meters]. There obviously must be something about this region right down here [Points to left part of graph] 'cause these guys [Waves

hand over C3, C4 lines] don't do very well there either, they peak about here [Points to C4 at 1400 meters], some there adapted to here, there's obviously something about very, very low elevations that is better for these guys [Points to C3] and these guys [Points to C4], somewhat, 'cause actually in terms of relative importance, that's really low elevation, maybe it's something to do with moisture, no, I don't know. Maybe there's a lake or groundwater that makes them grow well here [Points to left end of the graph].

Based on her experience, she subsequently suggested that the gradients of moisture and temperature indicated at the top of the graph possibly may not hold at the lowest elevations or that a lake or ground water levels provided the moisture to which C3 and C4 plants were adapted, therefore displacing the CAM plants.

Vernacular Situations

Some of the situations that were used as referents by the experts pertained less to situations from their professional life and more to their everyday life. For example, one expert described a familiar scene of going to the hardware store to buy lawn fertilizer. He suggested that fertilizers are carefully mixed, appropriate for the wanted application, so that he did not have to worry about mixing:

S01: When I go to the hardware store and buy bags of fertilizer they are very careful to put twenty to one or whatever the phosphorous–nitrogen mix is. This tells me that I don't need to worry about it. [He points to the x-intercept of the 50% line in Figure 1cii]. I can still grow grass at the same rate. I can still grow fifty tons of alfalfa with no phosphorous in the soil. It's just ridiculous.

As he pointed to the intercept of the 50% line with the abscissa (sign), he inferred that this implied grass or alfalfa could be grown without phosphorous (content), which any gardener or rural citizen knows, "is just ridiculous." Here, the situation that he inferred from a particular graph feature was inconsistent with his everyday knowledge of the world. In the following excerpt, the scientist suggested that he had seen isographs such as those in Figure 1c in the context of "welfare economics." This domain that had nothing to do with his work but he was familiar with it from the media:

S07: I've seen this kind of chart in like welfare economics and stuff, you know, where you're dealing with the inputs of two resources. [Pause] Like perfectly substitutable, so if- the level of one input can be off set by a certain level or another- You'd still be able to get your level of

> production or whatever. In real life, you know, a certain level of one resource doesn't necessarily equal that level of the other resource.

In this situation, although S07 (public sector) provided the normative reading ("perfectly substitutable"), he discarded the graph as useful because (perfect) substitutability is not a probable scenario.

When they were not familiar with the source of these graphs, scientists frequently engaged in the construction of common sense scenarios that could have given rise to a particular feature in the graph. For example, S15 (physicist) elaborated "rats in a cage" as a situation (content), drawing on the stereotypical behavior of rats and common sense, to evaluate birthrate and death rate curves when their number is increased. While interpreting the distribution graph, he drew a diagram that featured a mountainside with different types of vegetation, in the way he would have experienced it on one of his many hiking trips through the mountains. He also talked about the temperature decrease of about 1 °C for every 200 meters of elevation, again, a thoroughly experience-based understanding developed during hiking trips in the mountains. The use of everyday, common sense situations appeared to be used when the scientist perceived an unexpected element in the graph. For example, a number of scientists noted the increased relative importance of the C3 and C4 distributions at low elevations, which they read as inconsistent with the caption text ("CAM plants predominate in the hottest, driest environment"). In the following excerpt, one scientist produced a content model:

> S03: I'm a bit puzzled about this [Value of C3 curve below 900 meters]. I mean, you've got a range of frequency, which is, it doesn't- I mean and you got the same pattern here [Value of C4 function below 750 meters]. Something is going on at this end [Points to left side of graph]. There must be, there must be localized places where maybe it's in shade, depending on topography or whether some spring or something accounts for this relative abundance down here. Now, it's a, it is Big Bend National Park and I presume there is a river, a semi-desert, a desert and a semi-desert, so, this must be, maybe in the semi-desert areas that are similar. I mean, this [Points to C3 around 600 meters] has got an analogous point over here [Points to C3 around 1,200 meters] as does this [Points to C4]. So you can get, you can be in a hot dry place but still have shade and moisture which is equivalent to some place further up in the mountain.

In the course of his reading, S03 built a content model of the graphs at low elevations built on localized circumstances, including "shading," "spring," and "river," which would lead to the graphical expression at hand. Because S03 was unfamiliar with the specific park or the study from which the data were established, his description elaborated a possible world situation as the graph's content. However, because of the limited information provided with any sign, the specific world from which it might have been derived is underdetermined, and the set of possible situations can therefore be very large to infinite.

Graphical and Mathematical Models

We observed a number of individuals for whom the referents were not ecological situations but other mathematical and graphical representations. This was particularly the case for two theoretical ecologists (S09, S13) and two physicists (S01, S15) all of whom nevertheless also talked about types of ecological situations, hypothetical experiments, or vernacular examples involving biological organisms. In these cases, the modeling and representation aspects were the dominant concerns that shaped the reading of the graphs:

> S01: We are in Domain three because the initial population sitting up here is dying at a rate greater than it's been born, then over time you would have a decline in the population. It wouldn't be strictly linear because this is a power curve and this is linear. ...So, you have a family of curves that all do this, depending on what N is.

Here, S01 drew a family of curves representing the development of population size over time for the situation to the right of the upper equilibrium point (lower family of curves in Figure 3). In this case his drawing indicated, as did those of many of his peers, a collapse of the population (confirming an earlier verbal description). Although he perceived the functional dependency of birthrate and death rate on population density (i.e., b = b[N], d = d[N]), he did not see and therefore attend to the fact that birthrate and death rate, by definition, change population density. However, as he continued with his interpretation of the relation among birthrate, death rate, and their consequences on the population time graph, he changed his model but without explicitly marking this change.

> S01: If you were at these points here [Pause] you have a straight line across here, versus time. And this value which is a little higher, you'd also have a straight line versus time. It's an equilibrium. And if you get an N that's higher than that, then it would appear that's is going to drop, to drop off.

While attempting to map the equilibrium populations onto his own graph, he added two parallel lines above the previously drawn family of curves (i.e., in the course of elaborating the new graph with respect to the one provided, he arrived at correcting an earlier inference about the population as crashing). In the end, however, his inference in regards to using the population as a resource was non-

FIGURE 3 Diagram used by S01 to elaborate the population graph. At first, the lower family of curves represented the decline of populations larger than at the upper equilibrium. These were later redefined as the decline of populations below the lower equilibrium point:

standard ("As long as you could maintain your population between these two values, you should be able to use it as a resource, a fisheries resource"). During the session, he did not arrive at a satisfactory conclusion to this problem. Associating /logistic curve/ in the caption with "chaotic phenomena," he simply suggested, "But then you, that's when you get in this chaotic thing, it'd fall back down in this zone and it would be an equilibrium again I guess." Here, his verbal production chaotic phenomena became a new sign that influenced other signs present in the task (i.e., as contextual constituent) and therefore the outcome of his interpretation.

In another case, a scientist (S15), after identifying "stable equilibrium" and "unstable equilibrium," critiqued the representation as telling only part of the story. S15 suggested that the real content of the population graph was a system with a stable equilibrium and an unstable equilibrium. He suggested that in physics and chemistry, there were many cases of phenomena that had stable and unstable equilibrium points. S15 sketched the potential energy curves for NH_3, which flips between two stable states passing through an unstable equilibrium, the Leonard–Jones potential of an electron with one stable state, the potential of an atomic nucleus, and the potential of a chaotic pendulum. In all of these cases, the unstable equilibrium is associated with a local maximum in the potential energy and with (local) minima for the stable states. He pursued the hunch that birthrate and death rate function like forces in mechanical systems, and the fact that force is defined as the negative derivative of the potential energy $U\left(F = -\frac{dU(r)}{dr}\right)$. He then constructed an equation that he integrated to yield a potential energy curve for the population situation that resembled the curves he had sketched earlier for the physical situations. In his view, this new curve was a better representation of stable equilibrium and unstable equilibrium than the graph in the task. (Incidentally, S04 also provided /valley/ and /peak/ as interpretants of the equilibria.)

S15 suggested that another referent might be the "temporal evolution of a population." Again, this dynamic nature of the situation was not expressed in the original graph. He sketched out the problem as an iterative problem in which population size, death rate, and birthrate are updated according to

$$\begin{pmatrix} N_t + 1 \\ d_t + 1 \\ b_t + 1 \end{pmatrix} := \begin{bmatrix} N_t \cdot (1 + b_t - d_t) \\ d0 + d1 \cdot N_{t+1} \\ b0 + b1 \cdot N_{t+1} + b2 \cdot (N_{t+1})^2 \end{bmatrix}$$

Implemented in his mathematical modeling program, this iteration yielded a deterministic graph (Figure 4a). Because he expected oscillations, he therefore suggested that this model was deterministic and that, to get the expected oscillations, small random fluctuations to birthrate and death rate had to be added. By changing the initial value of N, he showed how the population tended to oscillate around the equilibrium value (Figure 4b), but close to the unstable equilibrium, could both collapse as well as eventually stabilize at the upper equilibrium (Figures 4c and 4d).

The two theoretical ecologists also suggested that the population graph was technically incorrect. It should have included a third, stable equilibrium at a zero population density where birthrate and death rate are zero. Furthermore, they analyzed the population graph, in terms of generalized functions, so that the conceptual content was irrelevant of the particular functions (and therefore shapes of the curves at hand) as long as the intersections were of a given type:

> S09: The strength of this graphical approach is that it doesn't actually matter exactly what these lines are doing as long as they interrelate with each other in this particular, in this general sense. So, this conclusion will hold true as long as these lines cross twice and the birthrate is temporarily above the death rate. And so the exact function of these equations is irrelevant. Mathematically, the model is very robust and you can change these functions any way you like and as long as the lines still do roughly that, it doesn't matter.

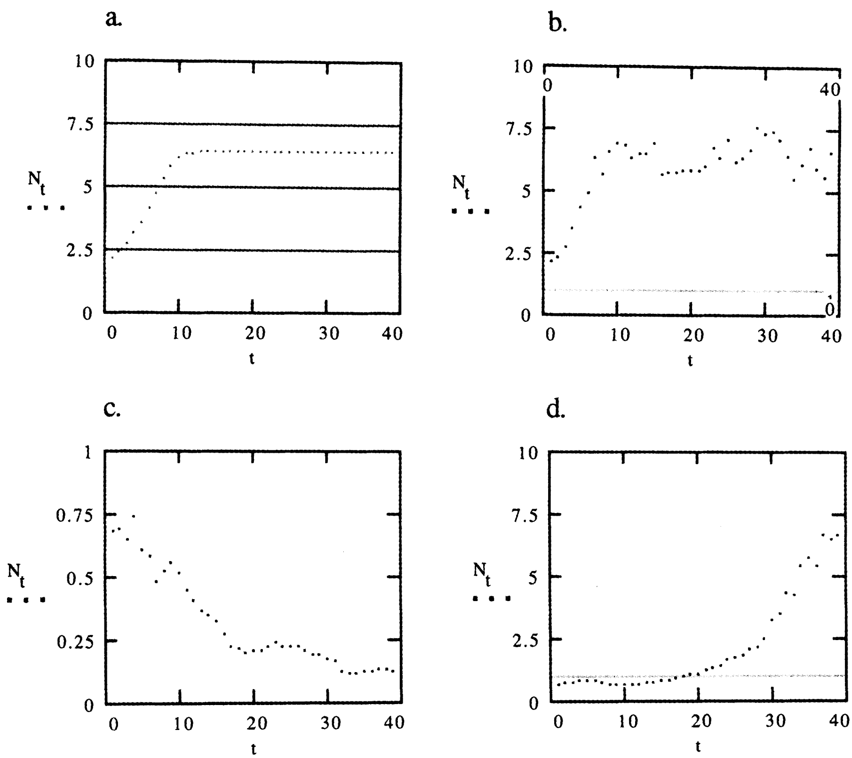


FIGURE 4 Four graphs produced by S15 to elaborate the population graph. (a) The deterministic model in which the population settles in the upper equilibrium. (b) Modified model with stochastic components providing a more realistic temporal development of population size. This modified model allows populations near the lower equilibrium both to collapse (c) or, less frequently, to move into the upper equilibrium (d).

Lacking (Realistic) Referent

In some situations, the scientists evaluated the graphs at a more global level and labeled the graphs as biologically unrealistic (didactic) cases that had little relevance or meaning in "the real world of science." Therefore, based on specific surface features, these scientists argued that there could be no meaningful referents in the real world, which is the main concern of their own work: The set of possible contents was an empty set. In this instance, the graphs were of little value to real science because they lacked important dimensions. The scientists variously indicated that graphs lacked scales and units of measurement or real data points. Some scientists also pointed out the simplistic topology of a particular curve, unconventional axis labels and other features, or the lack of stochasticity. For example, four scientists explicitly referred to the sharp corners in the essential resource graph (Figure 1ci) as biologically unrealistic (S01, S03, S07, S08):

> S03: In biology, we don't usually get that kind of a pattern, at least I'm not accustomed to seeing a pattern like this. [Pause] Here [Points to Figure 1ci] there's a mutual dependence, see at this point [Points to vertex of graph], R-one doesn't change, growth doesn't change, you get more of, it seems that this is simply a function, a concentration of the [Pause] I'm gonna give up on this, sorry.

Similarly, four scientists (S06, S07, S08, S14) suggested that the ordinate label /relative importance/ in the distribution graph [Figure 1a] interfered with a reasonable interpretation. For example, the marine mammal specialist S08 suggested the following:

> S08: Relative importance doesn't mean anything, until maybe I'll pick it up under here [Reads text]. But importance could mean everything from relative abundance to, you know, plants that bears like to eat, what's more important to them, there's, so really it doesn't mean anything to me.

S08 further suggested that he could not make sense of the distribution graph because he did not know the meaning of "the cryptic C-three and C-four." That is, although the signifiers C3 and C4 are part of introductory courses in biology, they had no significations for this scientist who was not working in botany. In the context of the population graph, S08 considered the notion of equilibrium as inconsistent with his own understanding of nature as a system that was far from any, even dynamic, equilibrium. Being a specialist of an endangered species, the complexities of population dynamics in the real world had become a primary concern to this scientist.

In a similar way, the population dynamics graph led some scientists to the conclusion that it was unrealistic. It did not portray natural variations in the rates (error) that might mislead interpreters (managers) to the (false) conclusion that populations are safe from extinction as long as they are above the equilibrium, however close. Others suggested that natural situations are much too complex to be modeled by a density-dependent function alone. Therefore, when scientists began with the assumption that a particular graph could not have a referent in the world, they already experienced interference in establishing possible referents.

Across the different graphs, about one half of the scientists treated the representations as having referents in the world; the other half treated them as models.

Those who treated graphs as referring to real states in the world experienced more difficulties in dealing with readings that conflicted either with states in the world they knew (as evidenced by S01 when his interpretation yielded a population equilibrium, whereas his real-world knowledge told him that oscillations are more likely than stable equilibria), or with other graphical signs and statements in the caption. Therefore, for those with modeling concerns, there existed degrees to which a graph could be mapped onto some state in the world so that the model could be inappropriate for a particular situation. S13 was typical for understanding the relation of such graphs to real populations and the kind of thinking processes that they support:

> S13: These are abstractions from data. At the beginning you have to understand that you have your x–y axis that- I kind of get a bit bitter about behavioral ecology by assuming graphs like this because they're really idealized, abstractions, a lot of times and they don't often, they don't always give sources even in textbooks. But I am assuming that this is some sort of fish population or something. You get that a lot. And what somebody has done in the past is gone out and measured, for a large range of population sizes, birth and death rates. Now, that's as you probably know like, it's a pretty difficult empirical problem sometimes to do that accurately because you don't always have a large margin of population that you have access to. But I'm assuming that what's going on here is that over a number of years, somebody has made an estimate of the mortality rates and birth rates in given population. And that this, I mean, this is not claimed to be data. I guess it's just showing that in a population given the birthrate looks like this and given the death rate that there is some linear function. What conclusions can you draw about the overall population size assuming that there's not many? I don't think it says anything about migration or anything like that. It is leaving out a lot of things. But given you have this idealized population and you know only two parameters about it, the birthrate and the death rate, and you're gonna vary this population size, what kind of predictions you can be able to make about the future change in population size?

When asked, these scientists stated that they worked implicitly under the assumption that "actual data" were noisy, that equilibria does not exist a singular values of N but as windows around individual points. For those with ecological concerns, the absence of explicit axis labels, identified organisms, and so on, meant that the graph was essentially meaningless and without interpretation.

Finally, some scientists suggested that one graph or another simply represented bad graphing practices (including S03, S05, S08, and S11). With respect to the plant distribution graph, S05 pointed out the following:

> S05: There's a fair a bit going on, I mean, they got this gradient up here [Points to gradient above the curves], hottest driest, coolest, least dry. Well, you know, for me there's a bit too much happening here. I mean, you have got the elevation scale and, your independent variable down there, and you've got ... [Pause] You know, I think, this graphing business, I mean, the simpler the better, and more concise the better, I mean, exotic charts are just not effective, I mean, maybe some researchers get carried away with that, and just a really simple.

Similarly, S03 found the plant distribution graph confusing, concealing more than it revealed:

> S03: He is taking something that's really simple and trying to make it look as confusing as possible, something that probably doesn't even need to be particularly graphed, or it could be graphed in another manner. Like his idea of putting hottest, driest, the coolest, least dry up there implies that that maybe separate from this elevation effect but they're actually not. [Pause] This thing conceals information that I would want and numbers of plants per square meter would be my preference because I don't get any impression of how abundant these plants are- how important they are to local ecosystems.

These excerpts show that some scientists found graphs (even the cognitively least complex graph) as difficult, confusing, and perhaps poorly constructed.

DIALECTIC AND ITERATION

In the previous examples, readers may have noted that the experts did not merely draw inferences but moved back and forth considering suitable values for referent and sign. The experts did not just elaborate signs, and thereby established possible referents; there was a reverse movement in the interpretation whereby participants used a new representation, a created model, or an example from the referent domain to explore the nature of the corresponding graph. For example, in S12's interpretation of the population graph in terms of the elk population in Banff National Park, the relation between graph and content (elk) was not unidirectional. Rather, he made inferences from the graph to natural populations as well as inferences from natural populations to graphs. Elements from the sign and referent domains constituted each other, being adjusted until the scientist felt a sense of coherence (i.e., interpretations did not just involve inferential processes from sign to content, but were dialectic processes where signs and familiar and possible content domains were used to constrain each other). In the earlier quoted scenario by S03 relative to the distribution graph, the shade, spring, and river that he made up are not only possible referents, but contribute to a reasonable scenario that could have given rise to the graph. That is, through a process of iterating between the source graph and its referent (as established by the individual, group), both sign and content were stabilized and thereby reified. Experts felt that they understood if they did not encounter snags in this movement between the two domains. Through this dialectic process, scientists also noted inconsistencies in their interpretations when there was no convergence in the two processes.

In the most general terms, then, we saw that there was a mutually constitutive relation between a graph (sign) and a corresponding content model (referent). In the interpretive process, scientists could begin with the sign and, in the light of any circumstances and familiar conventions, elaborate a content model, which could be either a natural situation, some hypothetical model, or another representation. Or they used their familiarity with some natural object ("you can be in a hot dry place but still have shade and moisture") to elaborate the sign form corresponding to it, given conventions and circumstances (the same value of the distribution and /relative importance/).

In our model, there are two component processes: structuring and interpreting. At first, it may appear that the structuring process must precede the interpreting process. However, there are cases in our database where scientists repeatedly returned to the structuring process, particularly when their attempts in finding appropriate {content, sign, context, rules} sets failed. They then sought new signifying elements so that the total set of features was not given but unfolded in time. Therefore, the two processes of structuring and grounding signs were interrelated such that, for example, the identification of an intersection as salient depended on the constituents. Signs and their constituents often were not perceived instantly, when individuals began to look at the task, but unfolded as the structuring process disclosed increasing amount of detail. Sometimes, individuals explicitly returned to the structural analysis, because the previously disclosed signs and the inferences drawn from them were inconsistent with the person's existing understanding of how the world works. Therefore, the two processes overlapped so that a feature may be immediately tested and grounded in outside references, and structural analysis could reoccur when a content model appeared to be problematic. This is evident from the following analysis where we return to S01's reading of the population graph. After having drawn his sketch, S01 began to doubt that he had completely understood the situation. In his world, the oscillation of population sizes around some average value is a truism. However, his model did not predict such oscillations:

> S01: I should be able to come up with some way that would go unstable but I don't see it right now. By unstable I would mean something that would, an oscillation that would put you sometimes above this curve and sometimes below it so that you didn't converge to this equilibrium.

He then inspected the graph, searching for a sign that indicated a process or feature that would turn the deterministic model (similar to Figure 4a) into an oscillating model of population size. In this search, he then identified different slopes as a possible feature that might introduce oscillations into his model. He marked a perpendicular line through b_{max}, labeled the left and right parts as Zone 2a and 2b and elaborated:

> S01: We can call that Zone two-a and two-b, because you're diverging from the death rate and here you're converging toward it. You probably—you could probably divide this one into an upper and lower portion and talk about slopes of convergence toward the equilibrium within that.

Prior to this episode, slopes had not featured in S01's reading and they did not feature in his reading of the other graphs. Here, it is evident that slopes became salient because he searched for a feature that would make his own graph oscillate and therefore be consistent with his familiar ways of seeing natural populations. In a similar way, the search for signs that bring their interpretation in line with a reasonable scenario encouraged them to isolate features not initially salient. For example, S02 had trouble with the notion of rate because, a priori, she did not distinguish between birthrate, $b = \frac{dN_+}{dt}$, and the derivative (slope, rate) of the birthrate, $\frac{db}{dN} = \frac{d}{dN}\frac{dN_+}{dt} = \frac{d^2 N_+}{dNdt}$. Similarly, S07 suggested that birthrate and death rate are equal, leading to a constant population size at that point where the slopes of b(N) and d(N) were equal and physically pointed to the approximate abscissa value where the two slopes were the same.

Finally, the slopes were perceptually salient for S04 when he wanted to quickly identify which intersections had stable or unstable population equilibria as referents:

> S04: So what you need is that the birthrate and the death rate are, have different, that the second derivative. No let's put it this way, that

> the first derivatives are of opposite sign, so that the slopes are, of opposite sign. So this is positive and this is positive so they are unstable. This is positive, this is negative, so it's stable.

In the process of explaining his model of the population graph for the Atlantic cod population, S04 introduced a somewhat vague interpretant /derivative/. In the course of his elaboration, he switched from drawing on /second derivative/ to /first derivative/. As he voiced this conjecture, he began to inspect the graph, more specifically to search for the derivatives (slope) at the three intersections. He finally arrived at the conclusion (of limited generality) that the slopes had to be of opposite sign. This is actually an invalid generalization. It is true in the case at hand and may be true for all practical purposes of an ecologist. One can easily draw counter examples in which slopes of opposite sign have an unstable equilibrium as referent, whereas the slopes of equal sign have a stable equilibrium as referent. A mathematically correct generalization reads as follows:

$$\text{sign}\,(N - N_{eq}) \times \text{sign}\,(b(N) - d(N)) \begin{cases} = 1, \text{unstable equilibrium} \\ = -1, \text{stable equilibrium} \end{cases}.$$

It is clear that this elaboration had not come from memory but was constructed from the situation at hand and the somewhat vague association with derivatives. Furthermore, derivatives (or slopes) that had not featured in his interpretation suddenly became salient; they became salient with the memory trace about derivatives and because of their potential as explanatory resources in the context.

FAMILIAR GRAPHS: TRANSPARENT READING

Scientists' readings changed considerably when it came to their own graphs, or if they were reading a familiar graph as part of a lecture or seminar in one of their undergraduate courses. When scientists read their own graphs (like literary authors might do to an interested audience), they usually began by providing a rich situation description, the content of the graph that they were asked to talk us through. The scientists then took the relation between their situation description and graph as self-evident. In some situations, they pointed to the graph (or some aspect of it) and suggested the visibility of some phenomenon related to the context that they had just elaborated in a narrative way ("As you can see … "). In other situations, they expected the interviewer to see the phenomenon without further assistance. A typical example for this structure in the reading of their own graph was produced by S07 while he talked about the graph in Figure 5:

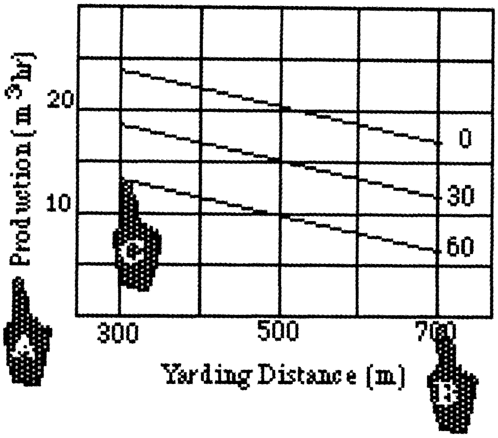


FIGURE 5 Graph from the work of S07, explained during the interview session. Lettered hands indicate locations pointed to.

1 S07: We did a production study about a new harvesting system that the industry is very much interested in but that they had known nothing about.

2 So we did a basic study to present information to the industry on how the productivity of this harvesting system can be estimated based on some key variables.

3 One of the important variables of course is the slope, yard, the distance that it takes to get a piece of wood from a mountain down to a landing.

4 To collect data for something like that you set up a production study and collect data and then plot it up, look for different relations between variables, and see the ones that are most significant.

5 In this case, you yard logs laterally to the system as well as yarding downhill. So, those are two important.

6 If you got a cable system that's spanning this valley where you've got a long skyline set up—a special type of yarding system on the mountain, which you can only set up so often—and you yard timber laterally to it and then down.

7 It just shows you graphically the results of this production function that we developed to give people a quick visual indication on what's involved.

8 Because people in the industry relate well to these numbers over here [Points to A], cubic meters per hour.

9 And they know now that if they got an area where they want to yard timber and its seven hundred meters, I mean, that's [Points to B] the furthest we collected data,from so that's where you gotta cut it off at.

10 You could be looking at production levels down around this area here [Points to C], twelve to fourteen cubic meters per hour, that helps you schedule your log trucks and you know you can understand your cost.

S07 began his account by situating his graph in a production study, and by describing the industry need to estimate their productivity. He then provided some scant details on logging operations, lateral and downhill distances, and core variables in his study (line 3). Already in the middle of his account, S07 added descriptive details of what a system looks like, a cable system and some way of logging laterally to the main cable (lines 5 and 6). Without further detail, he then explained how his graphs are used in the industry, where people "can relate well to these numbers" on the ordinate (line 8). He returned to describe in what range they had collected data (lines 9 and 10) before returning the value such a graph has to his clients ("that helps you schedule your log trucks," "you can understand your cost"). In this description, the graph was transparent in the account. S07 was so familiar with the circumstances that, although the study had been conducted some years earlier, he could see the situation while looking at the graph. He pointed to particular points on the abscissa (Figure 5B) or to a point on the graph (Figure 5C), but he talked as if he was actually out in the terrain where he had collected the data, right next to the logging trucks and skyline, neither machine being anywhere available on the graph or in the associated text. It was typical for all scientists to use phrases such as, "it just shows you graphically" (line 7), "you can see," and "see it's here."

In another case, S05 had explained the way (PCBs) got into an Arctic environment and how a subsample of PCB congeners was isolated using a gas chromatography mass spectrometer. He then pointed to three charts of a multiple bar chart representation, the first of which represented the fingerprint of the technical mixture in use. The second represented the fingerprint of PCB in the sediments at Cambridge Bay. He recognized that Charts 1 (original PCB mixture) and 2 (Cambridge Bay PCB mixture) were different ("a slightly predominance of these heavier congeners here and perhaps a few more," "in terms of pattern recognition, about similarities versus differences, at that stage, it kind of looks like hand-waving exercises"). However, he suggested that we should see that the fingerprints in Charts 1 and 2 were of a common origin by "kind of squinting at the relative size of the bars in these two graphs ... ":

S05: We can see just kind of squinting at the relative size of the bars in these two graphs that Cambridge Bay sediments kind of look like

> Aroclor twelve-fifty-four and therefore the primary source of PCBs to the Cambridge Bay sediments was the original spilling of this Aroclor twelve-fifty-four—sorry transformer fluid into Cambridge Bay.

He treated the two graphs the same ("for all intensive purposes they kind of look like the same"), despite making their differences apparent and despite suggesting the tenuous nature of similarity ("hand-waving exercises"). On the other hand, we should also see that Chart 3 was of a different origin, despite its apparent similarities with Chart 1.

In these explanations of graphs from their own work, scientists actually accomplished an inverse trajectory to that in their interpretive activities with the unfamiliar graphs. With the familiar graphs, not one scientist began by pointing to the graph, or highlighting and explaining some feature of it. Rather, all explanations began with the establishment of a rich experiential context. Therefore, during the interviews we learned about different logging systems, how they are set up, and about forest management techniques. We learned about the tracking of PCBs and arsenicals in the physical and biological contexts of Arctic environments, the differences between lipophilic and hydrophilic isomers, and mass spectrometry. Or, we learned about tracking ocean currents from the Atlantic through the arctic, about HDTs, laminate flow, and moisture carrying currents; or about pitch moth attacks, cloning effects, differential susceptibility for different tree species, and crop trees.

If signs are understood as tools (e.g., Brown & Duguid, 1992), then our results suggest that graphs with which they are familiar are not mere representations. Like tools in the hands of expert practitioners, signs begin to disappear. They are transparent in use and therefore allow the user direct access to a richly textured experience and accumulated knowledge. Nemirovsky, Tierney, and Wright (1998) described this disappearance in terms of the fusion of sign and referent. Users no longer distinguish between a representation and its referent. Territory and map, as Bateson (1972) suggested, are no longer treated as distinct but have been conflated. When experts operate at this level, their explanations of why and how they do what they do need to be treated with a grain of salt: What experts say they do and what they actually do turn out to be quite different (e.g., Bourdieu, 1990; Gilbert & Mulkay, 1984). In such situations, experts usually provide rationalizations. For this reason, we believe that the model developed by Tabachneck-Schijf et al. (1997) is limited to the specialized case where experts are thoroughly familiar with a graph—at this point, they do in fact talk about the paradigmatic elements of a graph crucial to the standard interpretation. However, the model is less likely to work when experts work with somewhat unfamiliar graphs because the rationalization of a fused sign–referent relation has not yet been developed.

DISCUSSION

This study was designed to better understand readings of familiar and unfamiliar graphs by professional scientists. Scientists are often used as a reference population, experts against whom other populations (novices) are evaluated. However, scientists are often intimately familiar with the domain of the task (e.g., Champagne, Klopfer, & Gunstone, 1982; Larkin, McDermott, Simon, & Simon, 1980) so that early expert research never separated innate skill from experience. More recent expert–expert studies made this separation (e.g., Patel & Groen, 1991; Wineburg, 1998), which allowed the distinction between specific and generic expertise. One may be tempted to argue that reading graphs is a general skill so scientists should be able to read them independent of contextual particularities. This study does not support this contention. The experts were far from perfect in providing more than a literal reading and arriving at standard inferences from the graphs despite two facilitating aspects of the graphs. First, the graphs in this study are similar to those encountered by students in an introductory ecology course; second, these types of graphs are standard for introductory textbooks on the subjects (both aspects that, one would think, would lead to these graphs being readily interpretable by the scientists).

Scientists' readings of their own graphs differed strikingly from those readings related to our tasks. In the case of their graphs, the graphical display provided transparent access to, and representations of, real-world situations. These situations were rich in texture that included conceptual and methodological aspects, and furthermore, historical, economic, and sociopolitical details of the context in which the data were collected. When scientists talked about their own graphs, they treated recognizable features as self-evident signs that signified objects, events, or phenomena in the familiar world of their research. Contrary to popular expectations, however, the experts in this study did less well (on the whole) when asked to interpret graphs that were not from their work place, such as the graphs typical of undergraduate level textbooks in ecology. With these they engaged in more or less extensive (perceptual) structuring of graph and caption. In some instances, they made sense by relating the graph to familiar phenomena or by constructing scenarios of phenomena that the graph might refer to. In other instances, scientists did not construct any external references, and their reading remained at the level of structuring the graph. It is not self-evident whether a particular feature of a graph signifies something. Rather, salience depends on the natural phenomena and the related experience of the interpreting scientist. Scientists also face situations where they do not know whether they had identified the relevant feature that serves as a sign to some content domain. When asked to identify that feature that would correspond to a particular phenomenon ("maximum number of individuals added to a population"), all but one scientist provided a nonstandard answer of the type that has traditionally been classified as a "perceptually based misconception."

Whether a geometric feature is salient appears to be in part a function of the constituents. For example, the intersection in the population graphs signify an equilibrium, not only because the graphs intersect but also because the two lines have /birthrate/ and /death rate/ as constituents. If the two curves each were marked /birthrate/ or /death rate/ of two different species, the referents of the intersections would be radically different. In this case, the intersections are of a similar kind as those in the distribution graph. The different locations of the distributions along the abscissa signify "differential adaptation" because of the underlying photosynthetic processes that allow plants to deal differently with environmental conditions. The same distribution curves, but in the context of body size or body weight of different populations (gender, race, age), have very different referents unrelated to "competition," "niche," and "adaptation." Therefore, one might expect these empirical results of higher salience of intersection in the population graph even if the text did not explicitly direct the participants' attention to it.

On the basis of this study we suggest that from the individual's perspective, graphs exist as the ensemble of salient elements; but the ensemble or matrix of elements frequently is not the same for two individuals. What and how we parse some focal situation (white paper with graph and caption) is not a property of the focal situation alone, but an interaction between reader and representation. In the past, not enough consideration has been given to the elements that are actually salient in the perceptual field of research participants and on which they base their interpretations. For this reason, it is not self-evident that a scientist should recognize the structural equivalence of two representations. For example, the representations S03 had brought to the session included 2-D matrices where each dimension mapped onto continuous variables collapsed into discrete categories; each cell contained the value of a third, dependent variable. Several lines in the matrix highlighted boundaries along which the cell values were equal. This matrix is a structural equivalent to the continuous isograph (Figure 1cii) that we had brought to the interview with the difference that in his graph, the continuous variables parsed into intervals. However, the scientist, in his interpretation of the isograph curves, had not recognized this equivalence. Furthermore, S01 had brought an article containing several very complex isocline graphs. He had no problems telling us how the data were collected, how the graphs were constructed, and what these graphs expressed. However, he did not arrive at the standard interpretation of the isocline graphs in this situation.

Tabachneck-Schijf et al. (1997) discussed the interpretation of a supply-and-demand graph that is of interest here because, at the intersection of the two curves in a cost–quantity coordinate system, it is conceptually and structurally equivalent to the upper intersection in our population graph (Figure 1bii). In their and our situation, equilibrium situations arise from the fact that there are opposing forces on some quantity at hand, product price (supply, demand), and population density (death rate, birthrate).[7] In contrast to their expertise, only 10 of the 16 scientists in this study provided a standard interpretation of the behavior of the population near the stable equilibrium. This apparently indicates that the interpretation of apparently simple graphs is context dependent and therefore aspects of specific rather than generic expertise.

Two aspects of traditional models of graph interpretation are questioned by the data in this study. First, our data do not provide evidence that individuals had to expend attention resources to death rate and birthrate or to the fact that the two constitute opposite tendencies. These were implicit contextual constituents in scientists' automatic treatment of the corresponding intersections as points of no population growth. Therefore, recognition of an environmentally given feature more readily accounts for the salience of constant population numbers at the two intersections. An increasing number of artificial intelligence and cognitive science researchers choose an ecological approach to external representations. They assume that in many situations the information in the environment is sufficient to specify all object and events, and the end product of perception is not a representation of the environment but rather that the invariant is directly picked from the environment without internal processing (Agre & Horswill, 1997; Zhang, 1997). Attention functions as a pointer system to enable deictic reference to the world that serves as its own representation (Ballard, Hayhoe, Pook, & Rao, 1997). In contrast to other models where representations are encoded in their entirety, Ballard et al.'s model represents only the useful portion (what is needed in this task) of what is visually available.[8]

Second, experts are said to recognize important features in the display, and having recognized them, interpret them meaningfully in the context of the problem at hand (e.g., Pinker, 1990). These data suggest that in domains where they know a graph very well (which is also the case for the economist in their study), scientists conflate them with the phenomenon itself. We pointed out the constituents of the work of interpretation, which were evidently different when the signs disappear in use. In (transparent) use, signs are no longer encountered as signs but as part of the background that allows people to lead meaningful lives; graphs are used to get the day's job done (Dreyfus, 1991). There is no more mental effort involved in using a graph than in drinking from a cup of coffee while writing a research article; in fact, we may not even be consciously aware that we are

[7]If the price is high, supply outstrips the demand, which tends to bring the prices down; if the price is low, demand outstrips supply, tending to bring the price up.

[8]Ballard, Hayhoe, Pook, and Rao (1997) and other recent work in the vision sciences (e.g., Churchland, Ramachandran, & Sejnowski, 1994; O'Regan & Noë, 2001) challenged the idea of Simon and his coworkers (e.g., Tabachneck-Schijf, Leonardo, & Simon, 1997). They suggested that the visual system does not always construct a full model of the scene (containing its parts as components and maintaining detailed location and shape information for each of the parts) and that the products of the perceptual computation are subsequently delivered to cognitive mechanisms for further processing.

drinking. Second, when the graph is not a simple index to some worldly phenomenon, scientists stabilize both phenomenon and their reading of the sign in an iterative manner. Interpretation, in the traditional sense of the word, therefore involves two tasks: reconstructing the internal dynamics of the graphical representation, and restoring to the graph its ability to project itself outside itself in the representation of a world that we can inhabit. Transparent use no longer involves the process of interpretation.

In some instances, the scientist used a hand as an additional representational device. In the population dynamics graph, a hand motion to the left accompanied population decrease, whereas an increase in the population was associated with a hand movement to the right over the inscription. In this way, very little internal processing appeared to be necessary, because the perceptually salient sign /d > b/ was elaborated by means of /the population decreases/, which was enacted in turn by the hand which served as a pointer in this situation. The pointer visually passed through the point earlier identified as an equilibrium point and thereby almost automatically leading to a correct interpretation of the intersection as having a stable equilibrium population as a referent.

In this study, we have taken each graph as a text (or matrix of signs) constructed of more than one sign element. Traditional lore might expect scientists to read these texts in such a way that some possible content emerges in which all signs are consistent with all others (i.e., we would expect scientists to work like Sherlock Holmes and, in a series of verbal and graphical productions elaborated during a session, specify a content model of a graph in which all elements are consistent such that some complex situation [content] is referred to by a series of signs). However, in a large number of cases, the scientists in this study did not use by default their readings of one sign to contextualize, and thereby constrain, the readings of other sign elements. For example, the possible readings of the abscissa label /N/ in the population graph and the ordinate label /relative importance/ could have been constrained by associating them with the reading of the signs "population density" and "distribution" in the associated caption.

Our research also throws into relief the claim that scientists use simple graphical models to reason about situations (Tabachneck-Schijf et al., 1997). The data provide evidence that field ecologists generally find graphical models, such as the population graph and the isographs, too simplistic to describe any real data set. Therefore, field ecologists question the usefulness of such models and do not work with them in the analysis of real situations and data. As one fishery scientist suggested, the size of last year's catch relative to that of immediately previous years is a more useful indicator of where to set fishing quota than any currently existing population model. On the other hand, those who model situations do not reason based on these graphs but rather in terms of more general concepts such as stable or unstable equilibrium.

CONCLUSION

Graphing has long been ranked among the archetypal scientific practices. Scientists' activities related to graphing have therefore been the touchstone against which the performances of other individuals have been evaluated. This study showed that rather than dealing with unfamiliar graphs in a self-evident way, scientists engaged in considerable work when interpreting a graph—and in many cases they did not arrive at the standard interpretation as defined in undergraduate courses and textbooks on the subject of ecology. Our study showed that even for scientists, there is work involved to

1. Link a graph to possible worlds by means of a complex inferential process.
2. Check whether or not an expression refers to the actual properties of the worldly things the graphs is speaking of.
3. Interpret expressions on the basis of certain coded or uncoded circumstances; this is inferential labor required to understand something and to the inferential labor required within the graph.

In contrast, when scientists worked with familiar graphs, these were seemingly transparent, allowing direct access to the phenomena the graph is said to be about. In our data base there are also instances where, because of previous related activities, the reading work lies somewhere between these two extremes. The fact that the scientists did not arrive by default at the standard interpretation should not be seen as an indictment of their inferential capacities. Rather, lack of familiarity with the particular representation, contextual constituents, underlying conventions, and the interpretive flexibility inherent in objects and signs, all contribute to underdetermine the endpoint of graph-related inferential activities.

Here at the end, we return to our initial question, "When are graphs worth 10,000 words?" Our research shows that when scientists are very familiar with some situation and its graphical representation, the graph (because of its transparency) constitutes an encoding (together with the familiar practices, circumstantial knowledge, etc.) worth 10,000 words. On the other hand, when they are unfamiliar with a graph, scientists spent not 10,000 but still between 1,500 and 3,000 words to elaborate an individual graph and what it communicates about the real or possible worlds. However, these words are important in a pragmatic sense in that they establish the full content an individual attributes to a sign, a process that is actualized by progressive reading; this progressive reading establishes the place individuals give graphs in their language.

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