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Polysemy in the Domain-Specific Pedagogical Use of Graphs in Science Textbooks: The Case of an Electrocardiogram

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Abstract Polysemy in graph-related practices is the phenomenon that a single graph can sustain different meanings assigned to it. Considerable research has been done on polysemy in graph-related practices in school science in which graphs are rather used as scientific tools. However, graphs in science textbooks are also used rather pedagogically to illustrate domain-specific textbook content and less empirical work has been done in this respect. The aim of this study is therefore to better understand polysemy in the domain-specific pedagogical use of graphs in science textbooks. From socio-cultural and cultural-historical perspectives, we perceive polysemy as irreducible to either the meaning-making (semiotic) resources provided by the graph or its readers who assign meaning to it. Departing from this framework, we simultaneously investigated: (a) the meanings 44 pre-university biology students assigned to the Cartesian plane of a graph that is commonly used as a pedagogical tool in Dutch high school biology textbooks (an electrocardiogram); (b) the semiotic resources provided by this graph; and (c) the educational practices of which it is supposedly a part according to the actions constituted by the textbooks that were to be conducted by students. Drawing on this case, we show polysemy in the pedagogical use of graphs in science textbooks. In turn, we show how this polysemy can be explained dialectically as the result of both the meaning-making resources provided by the textbooks and the graph-related practices in which students supposedly engaged by using their textbooks. The educational implications of these findings are discussed.

Keywords Biology education · Cultural-historical activity theory · Electrocardiogram · Graphing · Graph-related practices · Polysemy · Semiotics · Textbook analysis

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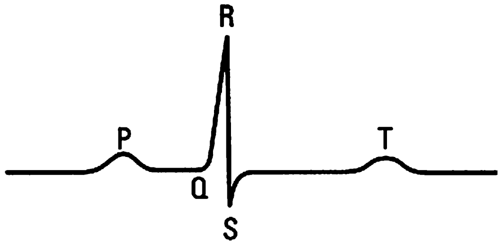
Introduction



31 *Electrocardiogram*

Heart graph—A physician can register the electric activity of the heart on the electrocardiograph with electrodes on the skin. Source 31 gives schematically the result: an ECG (electrocardiogram). During one heartbeat, the ECG of a healthy person shows three peaks. The P-peak reflects the electrical activity in the atria. Due to dissemination of the impulse over the ventricle walls the QRS-peak emerges. Refraction of the ventricles causes the T-peak. (Maier and Van Wijk 1999, p. 109, our translation)

Graphs such as the one above can be found abundantly in science textbooks (Lemke 1998). Despite their abundance, graphs are widely reported to be problematic in school science (Leinhardt et al. 1990). Recently, much work has been done in the anthropology of graph-related practices (Roth 2003). The outcomes of this work suggest that these difficulties have to do with *polysemy*, which is the capacity of a sign (e.g., a graph or text) to have multiple meanings (Ricœur 1974). For instance, the electrocardiogram above lacks many so-called graphing resources required for assigning a particular meaning to the Cartesian plane of the graph, such as axes and labels for units and quantities. Hence this graph is used in a way that is different from that in scientific journals (Roth et al. 1999). In the latter kind of graphs, many more resources are provided that collectively point towards a single interpretation. Thus, it has been suggested that graphs in school science textbooks are more polysemous than scientific graphs. This could explain many of the reported difficulties with graph-related practices in school science (Roth 2003).

However, graphs in science textbooks are not scientific tools. They are transformed (reshaped) from scientific texts to textbooks for specific pedagogical purposes and have other functions than graphs as research tools. For instance, the electrocardiogram is often presented as a 'neat' graph in textbooks to illustrate the working of the heart. Thus, for several pedagogical reasons, graphs can be used in specific ways to illustrate domain-specific content in textbooks.

Used pedagogically, a lack of graphing resources explains some of the difficulties students have when interpreting such transformed graphs (Bowen and Roth 2002). However, this explanation is only partial since polysemy cannot be entirely reduced to the graphing resources. The different ways in which students interpret a graph is also determined by the practices in which they engage in school science, among which those practices in which they use their textbooks and in which the graph is used as a meaning-making (semiotic) resource. Polysemy in graph-related practices should thus be understood dialectically and can be reduced neither to the semiotic resources provided by the graph nor to the reader of the graph who engages in graph-related practices. In this vein, less empirical work has been done on polysemy in graph-related practices in school science. The purpose of this study is therefore to better understand the dialectical nature of polysemy in the domain-specific pedagogical use of graphs in science textbooks.

In what follows, we provide salient background detail of research on the use of graphs in school science, including our theoretical commitments by which we understand graph-related practices as forms of human activity in which students engage by using the graph as a meaning-making (semiotic) resource. Based on these commitments, we articulate more specific research questions. Subsequently, we explain how we setup the case study to answer these research questions. Thereafter, we present the outcomes of our study. That is, we show polysemy in the domain-specific pedagogical use of graphs in science textbooks, which we explain as the result of both the meaning-making resources provided by the textbooks and the graph-related practices in which students supposedly engaged. We conclude this study by discussing its educational implications.

Background

Graph-related practices are common in school science; virtually every school science textbook contains many graphs such as the aforementioned. In this respect, school science parallels the work of professional scientists in which visualization by means of graphs and other inscriptions (pictures, diagrams, photographs, etc.) is considered a major aspect (Latour 1987; Lynch and Woolgar 1990). Graph-related practices are repeatedly problematized in science education research, not only because of their central position in school science, but also because they are reported to be problematic (Leinhardt et al. 1990). Research on graph-related practices initially focused on the use of graphs as research tools rather than rhetorical tools. In this research, two perspectives on the use of graphs can be distinguished, namely that as either cognitive ability or practice.

Graphing as Cognitive Ability

Early research on graph-related practices focused on the individual actions students performed with graphs, which were often called *graphing*. At the time, graphing was commonly taken as cognitive ability, that is, as a composite of individual cognitive abilities and skills, and graphs were viewed as mental representations (e.g., Marsh and Anderson 1989; Berg and Philips 1994). Such perspectives, however, led to a "common assessment problem of how to account for variations in performance across contexts and tasks, and a common attribution problem that locates difficulties in students' deficient cognitive apparatus" (Roth and McGinn 1997, p. 91). Ample research on graph-related practices showed that graphing, whether taken as an individual skill or ability, cannot be theorized apart from the collective practices in which individuals (students, scientists) engage (Roth 2003). For instance, case studies on students' understanding of graphs in mathematics classrooms revealed that particularly conversational resources such as the use of reference objects, spatial metaphors, and coordinated gestures and talk were fundamental to mathematically productive learning trajectories (e.g., Moschkovich 1996). More so, when professional scientists, who are considered experienced in graphing, are asked to interpret graphs that are uncommon in regard to their specific area of expertise, they exhibit difficulties with graphing of the same nature as inexperienced students (Roth and Bowen 2001). These outcomes parallel findings on the role of context in which individuals engage when accomplishing mathematical tasks (Lave 1988). Individuals' performance on mathematical tasks common in daily life showed little relation with their performance on tests in which the comparable tasks were stripped from the daily life contexts.

Graphing as Practice

Following the resulting situated perspective on cognition, the idea emerged that mathematical tasks such as graphing have to be understood in terms of practices—the patterned actions people deploy in their private and working lives—rather than as an amalgam of individual cognitive abilities and skills, stored in their heads that they bring to bear on problematic situations. Thus, it was proposed that students of mathematics and science should engage in activities that bear considerable family resemblance with the activities in which graphing is common and meaningful, that is, the activities scientists or mathematicians normally engage in (Brown et al. 1989). In response to such calls, researchers began to approach graph-related practices in both school science and professional science from cultural perspectives (Roth and McGinn 1997). Such perspectives allowed approaching the patterned actions students and scientists deployed in graph-related practices as being ethnic to school science and professional science in order to problematize in these practices that which was hitherto as taken for granted, namely graphing as practice. This work yielded a better understanding of difficulties with graph-related practices that plagued practical work in school science already for decades.

For instance, in one study in particular, researchers compared graph-related practices in high school biology textbooks with those in scientific ecology journals (Roth et al. 1999). Departing from anthropological perspectives, the researchers first developed an ontology of graphing, based on the graphing resources provided by the various graphs. These resources are required for making sense of the primary curve in the graph that traces the functional relationship between two sets of corresponding measurements. Such resources are axes and labels for units and quantities, the line of the graph, labels, scales (representations of quantities), units, plotted data points, difference markers that indicate particular aspects of the graph, legends and other aspects such as the main text and captions associated with the graph, which each facilitate graph reading. The ontology yielded eight different categories of graphs with decreasing graphing resources. The frequency of each of these categories was counted in both sections on ecology in six different high school biology textbooks and five annuals of leading scientific ecology journals. This analysis showed that "scientific journals provided more resources to facilitate graph reading and more elaborate descriptions and interpretations of graphs than the high school textbooks" (p. 977). Contrary to high school textbooks, scientific journals overwhelm the reader with many details that collectively "force" the reader to single interpretation—graphs in scientific journals are "constructed like some military strategy, an ambush without an escape route" (Bastide 1990, p. 208). Thus, by taking a situated cognitive perspective, it was shown in what respect graph-related practices in school science may differ from that in science with respect to degree of interpretive flexibility that was allowed. Rather than thinking graphing as cognitive ability, this framework could explain many of the reported difficulties with graph-related practices in school science (Roth 2003).

The Dual Nature of Polysemy

The differences in graph-related practices between high school biology textbooks and scientific journals centered on the allowed *polysemy*, which is the capacity for a sign (e.g., a graph or text) to have multiple meanings (Ricœur 1974). Polysemy in graph-related practices is for a great deal determined by the graphing resources. The fewer the graphing resources, the greater the polysemy, and therefore range of situations from which the graphs could have been derived (Roth 1996). Thus, a lack of resources provided by textbooks may result in an increased interpretive flexibility and hence a higher polysemy. As compared to scientific journals, graph-related practices in school science textbooks often constitute a relatively high polysemy. As a result, students—who are novice graph readers in the domain of science—may assign many other meanings to the graph than the one initially meant by the author and made available by the graphing resources in the graph. Graphing resources can thus be understood as interpretive resources: How the diagram should be read depends on the context, in particular the resources made available by the author.

On the other hand, interpreting a graph as a kind of text is a subtle interplay between the text and the reader and no text is capable of solely determining the outcome of the act of reading (Ricœur 1991). Even with professional graphs of scientists, many assumptions are inherent, which are generally understood as part of scientists' connoisseurship—much of which is tacit. The different ways in which readers interpret a graph is thus also determined by the practices in which they engage and in which the graph is used as a meaning-making (semiotic) resource. Indeed, as such, a graph like the ECG, like a text, can be considered a "limited field of possible constructions" (Ricœur 1973, p. 108). Polysemy in graph-related practices should thus be understood dialectically and can be reduced neither to the semiotic resources provided by the graph nor to the reader of the graph who engage in graph-related practices. This is observable in studies designed to investigate similarities and differences in collective graph-related interpretation between scientists and college students (Bowen et al. 1999). Guided by domain specific concerns, scientists' graph-related activities were characterized by a large number of experience based, domain-specific interpretive resources and practices, including extended periods of time working in the field—being part of a 'deep' community of practice, due to which they assigned particular meanings to graphs. They drew on a large stock of worldly situations to make judgments about the meanings of graphs that provided little graphing resources. Students' group based activities with the same graphs were characterized by the lack of linguistic distinctions between scientific terms which led to ambiguities in group negotiations. Specific knowledge of worldly situations, such as knowledge about specific organism populations which helped scientists to collectively assign particular meaning to the graph was not present in students' activities. The different ways in which readers interpret a graph is thus also determined by their past experiences, that is, the practices they usually engaged in and in which the graph is used as a meaning-making resource. As such, it became clear that graph-related practices in school science prepare suboptimally for dealing with the inherent polysemous nature of graphs as scientific tools (Roth 2003).

Pedagogical Functions of Graphs in School Science

Graphs in science textbooks can have specific pedagogical functions. One of these pedagogical functions is the focus of the aforementioned research literature and concerns how students learn to use graphs as scientific tools. However, especially in school science, graphs can have other pedagogical functions as well. These may have to do with general features of graphs as visualizations, such as the feature that students better memorize visualizations than texts (Mayer 2001). Other functions deal with illustrating domain-specific content to be studied by students. For instance, the electrocardiogram above is featured for at least three distinct reasons in sections on the heart and blood circulation in science textbooks. First, the graph is common in daily life, for instance in hospital scenes on TV. As such, it provides the opportunity to connect biological content, in this case on blood circulation, with students' daily life experiences. Second, as shown in the above example, the graph provides a means to explain the physiology of the heart in more detail, including its electric aspects. This is why in physiological textbooks the electrocardiogram is frequently featured simultaneously with the so-called Wiggers diagram, which is a graph that connects electrical phenomena of the heart to blood pressure and heart sounds (van Eijck 2006). Both the first and second pedagogical functions have to do with the learning of content via visualizations. However, the difference is that whereas the first function refers to the specific connection with daily life experiences provided by the ECG, the second refers to the primary function of a graph such as an ECG as an explanatory device. Finally, the third pedagogical function is that the context for the graph relates to students' daily lives. In itself, the medical relevance of this graph can be a reason for studying the graph in more detail. As well, the medical context provides another opportunity to illustrate specific biological content on the blood circulatory (e.g., van Eijck et al. 2004).

The aforementioned finding that differences exist between graph-related practices in high school biology textbooks and scientific ecology journals (Roth et al. 1999) may have to do with particular pedagogical choices made by textbook developers. They commonly copy graphs from academic journals or previous textbooks when developing new ones. In this process, graphs are transformed (reshaped, adapted) from research tools in scientific texts to pedagogical tools in school science textbooks. Inherently, however, graphs may lose several graphing resources by which polysemy increases. This, in turn, may explain why students have difficulties in interpreting such graphs, an explanation empirically warranted in the domain of ecology (Bowen and Roth 2002). The same process is likely to work as well in other domains, including that of heart and blood circulation. For instance, the electrocardiogram is often presented in textbooks as a 'neat' graph like the one presented in the beginning of this paper to illustrate the working of the heart (van Eijck 2006). Thus, for several pedagogical reasons, graphs such as the 'neat' electrocardiogram can be used to illustrate domain-specific content in textbooks in a more polysemous and rhetorical way than its genuine function as a scientific tool would allow.

However, as stated previously, polysemy cannot be entirely reduced to the graphing resources provided and should be understood dialectically. Hence the lack of graphing resources explains only in part why students may have difficulty in interpreting such transformed graphs. In this vein, less empirical work has been done on polysemy in graph-related practices in formal school science. For instance, little is known of polysemy in regard to graph-related pedagogical activities in which students engage by using their textbooks. Given this black spot in the research literature, the purpose of this study is therefore to understand better polysemy in the domain-specific pedagogical use of graphs in science textbooks.

Theoretical Commitments and Research Questions

In order to understand better polysemy in the domain-specific pedagogical use of graphs in science textbooks, we perceive it dialectically, that is, resulting from the transaction between the semiotic resources provided by the graph and graph-readers such as students who use and interpret the graph as a meaning-making artifact in graph-related practices.

This dialectical notion of polysemy entails both sociocultural (semiotic) and cultural-historical assumptions, based on which we constructed the design and setup of our study.

From a semiotic perspective, we perceive graphs in science textbooks (and their captions) as texts (Eco 1976; Saint-Martin 1990). As such, graphs constitute different semiotic modalities (e.g., text and inscriptions) that can each be regarded within a semiotic framework. At one level, this analytical framework maintains that representations such as graphs are texts that can be structurally analyzed in terms of their constituent resources and the relation of these resources. At this level, the reader sorts out which resources are actually "on the paper" and how these resources are connected with each other, but not yet what the constituent signs mean. This latter aspect happens at a second level, where the graphing resources are signs that refer to other material configurations (things) that people phenomenologically ground in the natural world (the signified or referent) (Ricœur 1991). An analysis of graphing thus begins with the act of reading and the (scientific) reader as an agent engaged in the analysis of graphing resources.

In turn, we assume that the act of graph reading as analyzing graphing resources (text, inscriptions) is shaped by the cultural-historical context of which this act is part. As a result, readings of a text differ with time and place and hence per individual engaged bodily in the act of graph reading. Graph readers participating in the practice of graph reading therefore turn up different text features and relations, and contextualize these features in different cultural-historically contingent ways (Roth et al. 2002). Therefore, we take graphing as human action in which graphs are used as meaning-making artifacts by individuals in the wider cultural-historical context in which they engage. Thus, this approach considers the individual act of graph reading as part of human activity and hence the latter as a unit of analysis (Leont'ev 1978).

Departing from these two compatible theoretical frameworks, we ask the question how polysemy occurs in the domain-specific pedagogical use of graphs in science textbooks as it emerges in the individual act of graph reading from the dialectical relation between (1) the graph in a textbook that serves as a semiotic resource for graph readers and (2) the use of a graph as a meaning-making tool in the wider cultural-historical context of the educational practice in which students engage by using their textbook.

Study Design

This study is part of larger study in which the teaching of quantitative concepts in pre-university biology education was studied and for which the domain of the working of the heart appeared to be an appropriate domain of study (van Eijck 2006). In this domain, the use of graphing resources was analyzed in the two most frequently used pre-university biology textbooks in the Netherlands (Maier and Van Wijk 1999; Smits and Waas 2001). This analysis revealed three graphs with (a) little graphing resources and (b) present in both textbooks. From these three, we selected the graph of the electrocardiogram (ECG) for the purpose of studying polysemy in more detail. Although we used the graph of one of the analyzed textbooks in particular, which is the one that is featured in the introduction of this paper together with its main text and caption (Maier and Van Wijk 1999), the graphs from both textbooks were highly similar with respect to the use of graphing resources (van Eijck 2006).

Answering our research question required a case study design that allowed us to relate students' act of graph reading to both the textbooks as meaning-making resources and the practices in which they engage by using their textbook. Initially, we probed polysemy as it occurs at the level on which students individually perform the act of graph reading. This is not to say that we probed polysemy in the classroom during instruction. Rather, for the purpose of our research, we investigated polysemy as the set of meanings students assigned to a graph after they had engaged in practices related to this graph as part of formal classroom instruction. Therefore, a task was designed based on the graph of the ECG. In this task, the graph was depicted on a sheet together with the text of the paragraph of the textbook in which was referred to the graph. Next, the question was asked: "Which quantities are measured and in which units are these quantities measured and hence which quantities and units should be noted at the horizontal and the vertical axis respectively?" This task was given to 44 students from three different urban schools following pre-university biology education (Grade 11, 16–17 years). Each of these students had followed a course covering the domain during which one of the aforementioned textbooks was used. The teachers of these students were experienced and all had a teaching experience of at least five years.

Next, we conducted two analyses in conjunction with each other to explain the observed polysemy dialectically. In the first analysis, we attended solely to the ECG and its immediate context made up of texts (signs) in the textbook as depicted in the previous example. Here, we analyzed how the graph in the textbook serves as a potential semiotic resource for graph readers. This is not to say that we probed how students actually used these resources when reading the graph. Rather, from the graph and its accompanying texts (signs) we inferred the meanings a graph reader potentially can construct from the signs provided. For this analysis, we drew on a semiotic analytic framework for interpreting inscriptions in science textbooks (Roth et al. 2005).

The second analysis focused on the use of a graph as a meaning-making tool in the wider cultural-historical context of the educational practice in which students engage by using their textbook. We selected texts from both textbooks that referred to an ECG. These extracts originated from the "Main text" and, in one textbook, in the "Enrichment" section. As well, those "Assignments" that referred to the ECG from both textbooks were selected. Table 1 lists these texts with their origin and the acronym which we will use in outlining the results of our analysis. Drawing on a heuristic grounded in cultural-historical activity theory (Engeström 1987), we inferred (extrapolated) from these texts the use of the ECG as a meaning-making tool in the wider cultural-historical context of the educational practice in which students engage by using their textbook. Thus, based on what we found in the textbooks, we envisioned the use of the ECG in the operational curriculum. This is a legitimate approach because textbooks have a highly authoritative role in the science curriculum and hence traditionally play the most significant role of all resources in formal

Table 1 Texts from the textbooks that referred to an ECG

Textbook	Texts	Acronym
Maier and Van Wijk 1999	Main text, p. 108	MVW1
	Assignment no. 14, p. 109	MVW2
	Assignment no. 15, p. 109	MVW3
	Assignment no. B, p. 112–113	MVW4
	Assignment no. B additional text, p. 113–114	MVW5
Smits and Waas 2001	Main text, p. 157	SW1
	Enrichment text, p. 192	SW2
	Enrichment assignment no. 1, p. 193	SW3
	Enrichment assignment no. 2, p. 193	SW4

science education (Goodlad et al. 1979). Indeed, it is well documented that teachers over-rely on textbooks when planning lessons (Weiss 1993). Thus, the selected textbook determines the scope, sequence, and depth of the lessons implying that from a textbook's texts the operational curriculum can be inferred.

The case study approach we opted for allowed us to analyze a single event in time and place from various perspectives, that is, in this case, graph-related practices through both semiotic and cultural-historical analytical frames. As such, we exploited the feature of case studies as a possibility to take the reader to a unique point of view. This allows one to look at the world through the researchers' eyes and to observe microdetails—in this case of graph-related practices—that one might otherwise not have seen (cf. Holland et al. 1995; Yin 1984). Such details can function as logical distinctions required for reframing the hitherto familiar world around us, which is a form of generalization (cf. Miller and Fredericks 2003). Through this process, which is known in the methodology of case study as naturalistic generalization (Donmoyer 1990), case studies overcome the issue of sufficient generalizability.

Polysemy in the Domain-Specific Pedagogical Use of an Electrocardiogram

In this section, we present the outcomes of our study. That is, we show polysemy in the domain-specific pedagogical use of the electrocardiogram in science textbooks as the set of meanings assigned by students to the Cartesian plane of an electrocardiogram. Subsequently, we explain the observed polysemy by the outcome of two analyses. The first analysis concerns the electrocardiogram as a meaning-making resource. The second analysis concerns the graph-related practices in which students supposedly engage.

The Set of Meanings Assigned by Students to the Cartesian Plane of an Electrocardiogram

Table 2 presents the outcomes of the task by which the polysemy associated with the ECG was probed among 44 pre-university biology students. One can observe polysemy as the set of different meanings assigned to the Cartesian plane. Regarding the horizontal axis little polysemy is observable, since most students identified its nature as reflecting the time in seconds. In contrast, students assigned varying meanings to the vertical axis, such as voltage, electric activity, and pressure. In particular, polysemy is observable as the variation in meanings assigned to the vertical axis of the graph.

The polysemy observable in Table 2 emerged from students' individual acts of graph reading. This is salient in light of the first part of our research question focusing on graphs in textbooks that serves as a semiotic resource for graph readers. These semiotic resources, such as axes and labels for units and quantities, help students to make sense of the Cartesian plane of the graph and hence the primary curve that traces the functional relationship between two sets of corresponding measurements. In this case, several of these semiotic resources are lacking, which may influence the set of meanings assigned to the Cartesian plane and hence explain the observed polysemy.

Graphs as Semiotic Resources: Description of Analysis

In order to explain the polysemy we probed, we performed a semiotic (meaning-making) analysis by which we came to understand how the meaning-making resources of the ECG contribute to the meanings assigned to its Cartesian plane. For this purpose, we adopted a

Table 2 Students' answers to the question to identify the nature of the Cartesian plane of a graph of an electrocardiogram

	Horizontal axis	Frequency	Vertical axis	Frequency
Quantities	time	38	voltage	7
	no answer	6	electric activity	17
			electric signals	1
			electricity	3
			current	4
			impulses	1
			pressure	5
			P, Q, R, S, T	1
			no answer	6
Units	ms	7	mV	4
	s	22	V	6
	MS	1	μV	1
	tenths of seconds	1	ΔV	1
	no answer	16	Ma	1
			mA	4
			a	1
			A	1
			N	1
			joule or watt	1
			Pascal	1
			kPa	1
			no answer	21

The numbers refer to the frequency of the respective quantity or unit that was counted in the answers of 44 students. Some students' answers contained multiple quantities or units

semiotic analytic framework developed for the understanding of inscriptions in science textbooks (Roth et al. 2005). Drawing on this framework, we start from the notion that a graph such as the one featured in the introduction in this paper, means little in and of itself. It contains details that allow many different ways of looking at and interpreting it. This detail provides a space that is continuous with our own lived world, allowing readers to establish a link with the everyday world that surrounds them. At the same time, graphs in textbooks provide cultural codes (lines, letter, and recognizable shapes) that could delimit their sense and meaning as intended by the author. To control the range of possible meanings to which representations in a textbook can give rise, authors construct inscription-text combinations that as ensembles constrain the sense readers can make.

From a semiotic perspective, the text and inscription constitute assemblages of two different sign or two different texts, where "text" refers more broadly to any entity that can be interpreted (Eco 1984). However, the two sign forms are not independent. Texts often refer to inscriptions and particular texts; captions always appear just below or next to an inscription. The two different and arbitrary sign forms are directly associated with each other. They are said to be about the same thing. For instance, the "electrocardiogram" caption is directly related to the inscription in the textbook about the graph. Caption and diagram are two of the three genres that constitute in this case the entire semiotic assemblage. The third genre is the main text, which is present nearby the graph as a paragraph of larger text about the working of the heart (MVW1).

We recognize the main text as belonging to the graph as it refers to “Source 31,” which features the same number as in the caption. Both in the sentence to which is referred to the graph and the caption, we observe the word “electrocardiogram,” which indicates similarity between what the main text and the caption are about. Indeed, this “electrocardiogram” is also what the inscription is “schematically” about. More so, the main text is titled “Heart graph,” which refers to the graphic genre, the inscription, and which is thus about the “electrocardio*gram*.” Recurrently, we learn also from the main text that the “ECG (electrocardiogram)” is “schematically” given by “Source 31.” Thus, the reader learns that each of the genres, main text, caption, and inscription are devoted to an “electrocardiogram.”

In the first two sentences, similarity is observable repeatedly between the sign that represents what this semiotic assemblage is about, namely the “electrocardiogram,” and other signs. For instance, the two devices with which the registration is performed, namely an “*electro*cardiograph” and *electro*des on the skin, and that which is registered, the *electric* activity, all implicitly refer to the *electro*cardiogram. Thus we learn that this graph has something to do with *electricity*. This electro*cardio*gram is also called “*heart* graph,” which is the result of the registration of the “electric activity of the *heart*,” with an “electro*cardio*graph” and which informs us thus that this graph is also about the *heart*. As such, the inscription becomes a sign that stands for the “electric activity of the heart” and is as such phenomenologically grounded in the natural world of the graph reader, who, as a pre-university biology student, has heard certainly about both electricity and the heart.

The inscription as a sign that stands for the electric activity is reinforced by what follows in the third sentence, in which we learn that the three peaks represent a “heartbeat,” that is, an active phenomenon that is common in the graph reader’s world. Following this and the next sentences, we observe another sequence of similarities in the signs present in both the inscription and the main text. The letters in the inscription (“P”, “Q,” ”R,” “S,” and “T,”) return in the main text (“P-peak,” “QRS-peak,” and “T-peak”) and the three peaks of the line observable in the inscription return as “three peaks” in the main text. From these similarities between signs in both the main text and the inscription, we learn that the peaks in the inscription are signs that stand for particulars of electrical activity of the heart that occur during a heart beat, such as “electrical activity in the atria,” and electrical activity that is “due to dissemination of the impulse along the ventricle walls” and “refraction of the ventricles.”

The Electrocardiogram as a Meaning–Making Resource

The previously illustrated analysis reveals a number of meaning-making resources that serve mainly as signs for assigning meaning to the primary curve of the graph rather than its Cartesian plane. More specifically, the graph features an assemblage of signs that stand for the electric activity of the heart and which ultimately point to the primary curve. Thus, we learn that the primary curve, with its peaks signified by letters, *is* the electric activity of the heart. This explains why many students, when asked what has been measured in this graph, refer to the electric activity or some other quantity that has to do with electricity. However, in graphs, this primary curve traces the functional relationship between two sets of corresponding measurements and is therefore defined by the meaning of the Cartesian plane of the graph. In this respect, the ECG as presented in the beginning of this article does not provide sufficient meaning-making resources in order to assign unambiguously a particular meaning to its Cartesian plane. In this case, the Cartesian plane is not defined as two sets of corresponding measurements and hence the graph is not constructed like an ambush without an escape route. Apparently, given the polysemy shown in Table 2, the ECG offers several escape routes along which students are allowed to assign different meanings to its primary curve. Precisely because the graph does not provide sufficient resources required for making meaning of the Cartesian plane as a functional relationship between two sets of measurements, the students come up with many possible answers when asked more specifically for referents to measurements, that is, quantities and units.

However, the graph and the main text are not isolated units. They are part of the textbook, which can be seen as a larger structure of meaning-making resources, that is, an artifact with a cultural-historical meaning. Collectively, these resources are meant to be used as tools in educational practices by means of which students assign particular meanings to the graph that go beyond those that can be inferred from the previous semiotic analysis in which we focused on the graph and its main text only. Thus, educational practices may help students to overcome the lack of meaning-making resources provided by the graph and its main text. Yet, apparently, these educational practices did not help the students to infer the meaning of the curve of the graph unambiguously. Focusing on the educational practices in which students are supposed to engage by means of meaning-making resources in the textbook brings us to answering the second part of the research question.

Graphing as Human Action: Description of Analysis

In order to understand better how the different practices in which students are supposed to engage by means of the ECG in the textbook support the students to infer meaning of it, we use cultural-historical activity theory (CHAT) as an analytic lens. CHAT is rooted in the work of soviet psychologists who maintained that human action cannot be understood outside actual praxis (Vygotsky 1978; Leont'ev 1978). It has become an important tool for theorizing and understanding complex systems of societally organized activities such as schooling (Roth and Lee 2007). Here, all forms of human praxis are conceived in terms of object-oriented and artifact-mediated activity. CHAT is concerned with understanding activity in the settings in which individuals engage, based on the grounds individual and collective human agents have for doing what they do. Activity theory aspires to understand and explain each form of action in its concrete material detail (artifacts, objects), whatever the situation, without loosing the connection to the organization of society into systems of activity. This theory allows us to analyze in more detail the educational practices constituted by meaning-making resources in textbooks such as an ECG and to analyze how human action is intelligible in such practices.

To analyze a concrete practice, researchers begin by articulating the activity and then ask what its constituent structures might be. Here, the originators of the theory do not use *activity* to denote what (science) educators commonly understand—e.g., doing an assignment—but in fact refer to a societal form of providing for the survival of all, such as farming or doing scientific research. Thus, the practice in which students engage by means of the textbooks is that of schooling, that is, reproducing cultural knowledge. One commonly used heuristic includes six basic conceptual entities: subject (individuals or groups), object (artifact, motive), means of production (including instruments, artifacts, and language), community, division of labor, and rules (Engeström 1987). In Fig. 1, we exemplify this heuristic for the analysis of educational practices constituted by the ECG in the textbook. None of these six entities can be studied in isolation from its current (a) material and cultural and (b) historical context, because in a particular concrete activity, the subject (which schema are brought to bear) and the relevant object (which material structures are currently relevant) presuppose one another (Leont'ev 1978).

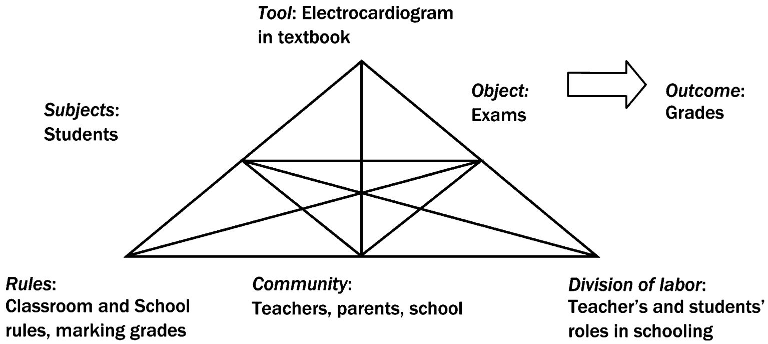


Fig. 1 Example of CHAT-heuristics: analysis of the educational practice in which an electrocardiogram is used as a tool

To understand and theorize any moment of human activity, three concurrent levels of events need to be distinguished: activities, actions, and operations (Leont'ev 1978). In CHAT, actions play a special role, because this is what human individuals bring about and what researchers observe. The texts in the textbooks we analyzed basically constitute two types of actions: reading texts and completing assignments, where the latter can be divided into writing answers to queries by using text and setting up and conducting the measurement of an ECG. These are typical actions, for they realize conscious goals articulated by individual students. An action implies both physical (bodily) involvement—e.g., observing a graph while reading it—and participation in societal activity (schooling). Actions also imply acting subjects and objects acted upon. Actions only make *sense* with respect to the particular activity, because in a different activity it will have a different sense—using the same graph in science or schooling realizes different goals, has a different sense, and has different outcomes (Brown et al. 1989). Actions do not constitute the lowest level in the analysis. Every action is composed of a sequence of operations, of which the goals are not consciously experienced by the subjects. Hence this dialectical relation between action and operation is one of *reference*; simultaneously, operations realize actions concretely and the latter functions as the mould for the production and sequencing of operations (Roth 2005). For instance, while reading an ECG such as featured in the beginning of this paper, reading and sequencing the letters P, Q, R, S, and T is not a conscious act, but we unconsciously interpret these letters as a series in the alphabet while reading the graph in its entirety. Attributing *meaning* to something like a graph or text follows from the dialectical relation between sense and reference. Thus, meaning is simultaneously rooted in the bodily synthesis of operations into actions, and in the social significance of actions in regard to the entire activity (Roth and Lee 2006). Sense and reference, and therefore meaning, are inherent to actions rather than texts; that is, for instance, neither an ECG nor its primary curve has sense or meaning in itself. They emerge in and are the results of actions the students perform with textbooks, for instance by reading texts and completing assignments in which the ECG is used as a tool or is the outcome. Then, in the act of reading, individual words and phrases can provide reference as they become signs for human action articulated by the collective text they constitute (Ricœur 1973).

Thus, we asked the analytical question which actions are potentially mediated by the selected texts in the textbooks and how in such actions sense and reference are established by which students attribute meaning to the ECG. Regarding reference, the link between operations and actions is established by individual words and sentences referring to characteristics of the primary curve that collectively make up the entire text that can be considered as an account of human action. Regarding sense, the link between actions and activity is established by a discourse that refers to the way in which characteristics of the ECG play a role in human activity.

For the purpose of exemplifying our analysis, we consider the main text of the electrocardiogram given in the beginning of this paper (MVW1). This main text constitutes the act of reading. In this act, reference is established by individual words referring to the nature of the primary curve of the ECG, such as “electric activity,” the letter “P,” which is the “electrical activity in the atria,” “QRS,” which emerges due to the “dissemination of the impulse over the ventricle walls,” and “T,” which is the “refraction of ventricles.” Also in this text, sense is established by referring to the practice of the physician. Accordingly, we performed this analysis for all the texts referring to the graph of an ECG in both textbooks.

Graphing as Human Action: The Electrocardiogram in Educational Practice

In Table 3, we present an overview of the outcome of the previously illustrated analysis. The contents of Table 3 reveal salient detail in regard to the observed polysemy of the ECG featured in the previous section, which have to do with both the reference and the sense as established by actions that are supposedly to be conducted by students and supported by the texts of which the ECG is a part. The actions supported by the texts in which ECG is used as a tool refer to phrases such as “electric activity” or “nerve impulse propagation,” but do not explicitly make clear how this is measured and/or related to the ECG [MVW1–5, SW1-3]. Further, there are references to specific patterns in the primary curve, such as “P,” “QRS,” and “T,” which are in turn related to “activity” of specific parts of the graph, but these texts do not explicitly establish reference to the relation between these patterns and either the way in which an ECG is measured or the nature of the Cartesian plane of the ECG [MVW1–5, SW1, SW3]. Regarding the nature of the horizontal axis, reference is established in more detail. For example, actions supported by the texts in which the ECG is used as a tool refer to time in milliseconds [MVW3–5]. In only one textbook, the actions of which the ECG is an outcome supported by the texts directly establish reference to measuring the primary curve of an ECG [SW4]. However, it is only present in one of the two textbooks as an extra enrichment assignment and not part of the compulsory part of the textbook. More so, the use of microcomputer-based laboratories as featured in the text is limited in pre-university biology education in the Netherlands (van Eijck 2006). Therefore, it is unlikely that all students have participated in these practices.

Regarding the establishment of sense, only in one textbook the actions supported by the texts in which ECG is used as a tool refer to practices in which the ECGs are used or measured, such as those of the physician and the scientist. However, these actions do not articulate how the nature of the Cartesian plane of an ECG is exactly playing a role in those practices [MVW1, MVW5].

The outcome of this analysis of the texts with an ECG that constitute actions the students are supposed to conduct explains why the educational practices did not help students to overcome the lack of meaning-making resources provided by the graph and its main text effectively. For instance, little information is provided to indicate what is represented by the vertical axis of the ECG. This may explain why many students do not specify the vertical axis of the ECG as representing the measurement of the quantity voltage in units Volt (see Table 1). Instead, they refer mainly to “electric activity” or other phrases that are featured repeatedly in establishing reference in the texts of both textbooks. More so, exactly those terms and phrases that are used to provide reference based on which students are supposed

Table 3 Types of potential actions supported by texts in textbooks referring to the ECG and the way in which in these texts reference and sense are established potentially by which students can assign meaning to the primary curve of the ECG

Text	Actions	Reference	Sense
MVW1	Reading	Refers to ECG as electrical activity	Refers to practice of physician
		Refers to P as electrical activity in the atria	
		Refers to QRS as dissemination of impulse over ventricles	
		Refers to T as refraction of ventricles	
MVW2	Reading, Writing	Refers to text MVW1	–
		Instructs students to write down which peaks of ECG will show irregularities that point to failure in nerve impulse propagation by AV-node	
MVW3	Reading, Writing	Refers to text MVW1	–
		Instructs students to place ECG on same time scale as pressure-time graph of left ventricle	
MVW4	Reading, Writing	Instructs students to rewrite text MVW5 to a scientific report	–
MVW5	Reading	Refers to many animals measured by scientist of which ECG is measured, among which elephants that got battery clamps as electrodes	Refers to practice of scientist
		Refers to PR-time	
		Refers to PR time in milliseconds	
SW1	Reading	Refers to nerve impulse propagation measured with ECG	–
		Refers to P as nerve impulse propagation of atria	
		Refers to QRS as nerve impulse propagation ventricle wall	
		Refers to T as recovery period of cells in ventricle walls	
SW2	Reading	Refers to ECG that can be used to detect failure in nerve impulse propagation by observing irregularities	–
SW3	Reading, Writing	Refers to text SW2	–
		Refers to R and S in ECG	
		Instructs student to write down with which letters nerve impulse propagation in the atria and ventricles are indicated	
		Instructs student to write down to which heart failure in nerve impulse propagation two different irregular ECGs point	
SW4	Reading, measuring ECG	Instructs student to measure ECG by means of electrocardiograph	–

to attribute meaning to the primary curve of the ECG can be found in their answers presented in Table 1, such as the quantity pressure or the terms “P,” “Q,” ”R,” “S,” and “T.”

Coda

Our detailed study showed polysemy in the domain-specific pedagogical use of an electrocardiogram (ECG) in two commonly used Dutch biology textbooks. That is, polysemy was observable as the set of different meanings students assigned to the Cartesian plane of the ECG from their textbook which they had used previously during formal instruction in the domain. In turn, we showed how this polysemy can be explained dialectically as being the result of both the meaning-making resources provided by the textbooks and the graph-related practices in which students supposedly engaged by using their textbooks. On the one hand, detailed semiotic analysis of the ECG of one of the textbooks showed that it does not provide sufficient resources required for making meaning of the Cartesian plane of the ECG as a functional relationship between two sets of measurements set out along its axes. Thus, the ECG offers many escape routes along which students are allowed to assign different meanings to its primary curve. On the other hand, analysis of the ECG-related educational practices constituted by the textbooks showed that these potentially do not establish the sense and reference required to overcome the lack of meaning-making resources provided by the graph and its main text. Thus, in establishing polysemy, the educational practices in which students supposedly engaged complement the lack of graphing resources of the ECG.

This dialectical explanation of polysemy allows us to understand the difficulties that arise when students assigned a meaning to the Cartesian plane of the ECG even after formal instruction. Accordingly, we can envision the tools required for countering the observed situation. That is, in this case, we can distinguish several means by which we might decrease the observed polysemy in the domain-specific pedagogical use of an ECG like the one in this study. In regard to the ECG as a semiotic resource, it would help students to use in the textbooks an ECG in which an increased use of meaning-making resources provides less escape routes along which students can assign meanings to its Cartesian plane other than a functional relationship between voltage (in mV) and time (in ms), such as axes, and labels for quantities, units, and scales. These suggestions are comparable to suggestions made after studies on graph-related practices in ecology textbooks (Roth et al. 1999; Bowen and Roth 2002).

However, considering only a graph and its main texts is not sufficient for understanding why polysemy occurs in graph-related practices. In addition, based on the analysis of the educational practices constituted by texts in textbooks other than the main text, we maintain that students should engage in graph-related practices in which sense and reference are established. Such practices can be supported by contemporary pedagogical tools specifically designed for the purpose of measurement, such as dataloggers (e.g., Russell et al. 2003; van Eijck et al. 2005). In the context of this study, such practices may help students to attribute meaning to the ECG in more salient detail and more purposefully. For instance, one of the assignments of one of the textbooks instructs students to measure an ECG by themselves. This may provide a means for the establishment of a reference required for attributing more detailed and unambiguously a meaning to the primary curve of an ECG [SW4]. Indeed, the use of commensurable graph-related practices with microcomputer-based laboratories shows a polysemy of an ECG lower than in this case (van Eijck 2006). We therefore recommend assignments such as these to be part of the introduction of the ECG in textbooks.

Despite the many possibilities for reducing the polysemy of the ECG in this particular case, it is important to realize that even in the domain-specific pedagogical use of graphs in science textbooks, polysemy in graph-related practices cannot and should not be reduced to zero. Every artifact or text such as an ECG is a limited field of possible constructions (Ricœur 1991). That is, as long as different human individuals are involved, there is always the possibility that different meanings are attributed to a sign such as the ECG. Indeed, in practices in which the ECG is used, such as science and medicine, practitioners may attribute different meanings to particular ECGs. For instance, in medical cases, ECGs of patients to which different cardiologists attribute different meanings can become cases for further research. Thus, while initially meant to be a tool for diagnosis, a particular patient's ECG can become an object of research, thereby showing movement between the different moments of activity (from tool to object) and practices (from medical to scientific practice), which is a common cultural-historical dynamic in human activity (Engeström 1996).

Thus, rather than reducing polysemy to zero in the domain-specific pedagogical use of graphs in science textbooks, science education should be more commensurable with the inherent polysemous nature of human activity and allow the possibility of non-intended outcomes or changes of practice. Indeed, one of the aims of science education should be that students learn to explore the epistemological foundations of knowledge claims. Thus, in this case of graph-related practices, students should learn that the polysemous nature of the graphs in their textbooks reflects an ambiguousness that is inherent to all knowledge claims, including those made by professional scientists. Unless science education does not include such a reflexive component which allows students to critically evaluate the knowledge claims of a particular field, they will always be subject to some form of indoctrination (Désautels and Roth 1999). Thus, for science education to contribute to developing students who are able to reflect critically on knowledge claims, polysemy should be purposefully nurtured in the domain-specific pedagogical use of graphs in science textbooks.

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