Comprehension of Graphics

Wolfgang Schnitz
Raymond W. Kulhavy

Advances in Psychology

108

North-Holland
COMPREHENSION OF GRAPHICS

Wolfgang SCHNOTZ
Institute of Psychology
Friedrich Schiller University of Jena
Jena, Germany

Raymond W. KULHAVY
College of Education
Division of Psychology in Education
Arizona State University
Tempe, AZ, USA

1994
NORTH-HOLLAND
AMSTERDAM • LONDON • NEW YORK • TOKYO
With Contributions by

Linda C. Caterino, Michel Denis, Günter Dörr, Johannes Engelkamp,
August Fenk, Marie-Dominique Gineste, Camilla Gobbo,
Valérie Gyselinck, Michael Henninger, John R. Kirby,
Raymond W. Kulhavy, Abdellatif Laroui, Ulla Maichle,
Richard E. Mayer, Mark A. McDaniel, Gilbert Mohr, Phillip J. Moore,
Joan Peeck, Emmanuel Picard, Frédérique Robin, Jill Scevak,
Wolfgang Schnottz, Norbert M. Seel, William A. Stock, Hubert Tardieu,
Paula J. Waddill, Bernd Weidenmann, William Winn,
Hubert D. Zimmer, Michael Zock
This page intentionally left blank
Preface

Graphic displays like charts, graphs, diagrams, and maps play today an important role in the design and presentation of instructional materials education. There is also a strong need in scientific, technical and administrative fields to visually present certain facts, laws, principles etc. In recent years, the use of computer-based learning environments has also become an important field where the visual presentation of information plays a central role. Despite the importance of graphical displays as a means of communication and despite the fact that research about learning and cognition has advanced rapidly in the last two decades, the comprehension of graphics is still a rather unexplored area. Many studies have shown that graphics can make communication and learning more effective, but we have only recently begun to understand better why and under what conditions they are really effective. The comprehension of graphics is not only a stimulating topic in the fields of science and instructional psychology, but also of related disciplines like semiotics, and artificial intelligence. Research on the comprehension of graphics complements the scientific investigation of cognitive processes in text comprehension, which has contributed much to our understanding of human cognition and learning. Ultimately, a better understanding of the cognitive processes involved in the comprehension of graphics will have an impact not only on cognitive theory, but also on educational practice.

In order to stimulate theoretical and applied research on comprehension of graphics, a conference on Comprehension of Graphics was held at the Learning Research Department in the German Institute of Distance Education at the University of Tübingen from October 29 till 30, 1991. The aim of this conference was to provide an opportunity for scientists from different countries to exchange theoretical approaches and empirical findings and to discuss new research perspectives on the comprehension and knowledge acquisition from graphics. In addition, the conference was initiated to stimulate international co-operation within this field of investigation. Participants of this conference came from Australia, Austria, Canada, France, Germany, Italy, the
Netherlands, and the USA. The conference was initiated and organized by the first editor, and financed by the Volkswagen foundation.

The conference was organized as a working meeting with research presentations followed by discussions involving all participants. The papers presented in this volume are the result of these presentations and the subsequent discussions. The papers have been grouped into four sections: (a) graphical codes and graphics processing, (b) graphics and mental representations, (c) differential and developmental aspects, and (d) instructional aspects.

**Graphical codes and graphics processing**

The first section concerns the relation between visual codes appearing in stimulus materials and cognitive processes that are triggered by these codes during the comprehension of graphics. In chapter 1, Winn provides an overview of the state of the art in research on graphics comprehension. He describes the interaction between the preattentive processes of detection, discrimination, and configuration of visual signs on the one hand and the concept-driven, schema-directed attentive processes on the other hand. Winn points out the relevance of culture-specific processing habits, like, reading from the left to the right, which strongly influences the understanding of graphics. Referring to his own studies, he demonstrates that graphics can considerably enhance problem solving behaviors by providing individuals with a two-dimensional display of problem structures.

In chapter 2, Weidenmann analyses different kinds of graphic codes and their relevance for graphics comprehension. A basic distinction is made between depicting and directing codes. Whereas depicting codes have a representational function, directing codes guide cognitive processing without directly representing depicted facts. Since graphics are often processed only superficially and their semantic content is only vaguely described verbally, the special function of directing codes is to trigger certain kinds of cognitive processing. Weidenmann points out that directing codes should not be interpreted as equivalent to the schemata of general perception. Rather, the learner has to grasp the communicative intentions of the author by mentally reconstructing the author's visual argument. A better understanding of the function of graphical codes can be considered as an essential basis to enhancing visual literacy and to adequately combining verbal and pictorial information during instruction. For future research, Weidenmann
suggests investigations of the relation between various graphic codes and subsequent cognitive processes that these codes activate during graphic comprehension.

In chapter 3, Fenk analyzes a special aspect of graphical codes: their relation to the metaphorical content of natural language. Referring to Peirce’s distinction between symbolic signs, iconic signs, and indexes, Fenk demonstrates that so-called logical pictures like graphs and charts do not have an arbitrary structure entirely determined by conventions. According to his point of view, graphical codes should be considered as externalized spatial metaphors derived from language. In two studies, Fenk demonstrates that the closer the structure of a logical picture corresponds to an appropriate metaphor of language, the easier it can be understood. Such a relation between logical pictures and linguistic spatial metaphors is not only relevant for our understanding of graphics comprehension, it can serve also an important heuristic function. One implication of Fenk's position is that graphic designers should refer more explicitly to the predominant linguistic spatial metaphors in their culture.

In chapter 4, Kirby examines the question of how graphical maps are cognitively processed. He proposes a distinction between holistic and analytical strategies of map processing. In the former strategy, a map is considered as a coherent spatial structure, wherein structure is processed visually with special consideration of spatial relations between its elements. In the latter strategy, a map is processed using verbally-oriented mechanisms that target various elements in the map. Different levels are assumed within both kinds of strategies. Kirby relates the holistic and the analytical strategy to different dimensions of cognitive processing, which can also be combined to each other. The ability to switch flexibly between holistic and analytic processing or to combine them flexibly according to actual demands seems to be a central point in comprehending graphics. Kirby points out that learners seem to have difficulties spontaneously carrying out higher order holistic and analytical processing.

In chapter 5, cognitive processing of graphics is approached from another perspective: Denis, Robin, Zock, and Laroui examine how individuals analyze and verbally describe visual displays of different complexity. The authors demonstrate that generating a verbal description of a holistic two-dimensional structure is subject to the constraints of cognitive economy: When describing non-linear graphical structures, individuals try to reduce the required cognitive processing capacity by minimizing the number of elements to be stored in working
memory and by keeping storage time as short as possible. Denis and his colleagues demonstrate that optimal descriptive sequences require a sufficient analysis of the graphical display by the subject. Finally, the authors outline a computer model for describing complex graphical displays, and which can serve as a tool for the examination of psychological assumptions about graphics processing by combining simulations and experiments.

**Graphics and mental representations**

The contributions of the second section investigate relations between cognitive processing initiated by graphical codes and mental representations constructed as a result of this processing. A central point of this section is the question of how graphical information is mentally represented. In chapter 6, Zimmer examines a multimodal memory model developed with Engelkamp. The model distinguishes between a visuo-spatial subsystem, a conceptual subsystem and a motor subsystem. Zimmer assumes that the visuo-spatial subsystem can be used for the processing of visual as well as the processing of verbal input. Accordingly, learners can construct similar mental representations using either verbal or graphical information. Processing proceeds differently, however, depending on whether information about features or about spatial relations is more important. Zimmer demonstrates that graphical information is automatically processed in the visual subsystem, but that use of the resulting mental representation depends on the task at hand. Accordingly, Zimmer argues that the use of graphics does not, per se, facilitate learning. The essential point is which cognitive subsystem encodes which kind of information and to what extent the resulting mental representation is suited for coping with the respective problem. Zimmer also points out that it remains unanswered whether learners create exocentric representations for some problems and egocentric representations for others or whether exocentric representations are generally preferred.

In chapter 7 Engelkamp and Mohr examine how different forms of visual and verbal information about size differences affect memory. The assumption is made that such information can be mentally stored both in a spatial representation of the visual display as well as a spatial representation of the entailed size differences. Accordingly, both forms of representation can be congruent or incongruent with each other. The authors demonstrate that with incongruent representations the data are similar to results yielded by using verbal representations only. The
authors interpret their results as follows: graphical information on size differences can be directly encoded in a visuo-spatial code and then be directly read from it. Further, dual encoding in visual and verbal forms does not always take place, or such dual encoding won't be used in every case. Thus, graphics offer the possibility of constructing both a spatial mental representation and a propositional representation, but in order to ensure that this possibility is efficient, it is important that the learner has access to the required mental representation.

In chapter 8, Mayer examines the question under what conditions graphics aid learners to understand the function of technical devices. He assumes that learners understand the function of such devices when they are able to construct appropriate mental models. Such models entail representations of the components of the device and causal relations between these components, so that a change of the state in one component leads to a change of state in other component. The author argues that the formation of such a model requires that the learner constructs representational links between graphical information and the respective mental representation, representational links between verbal information and the respective verbal mental representation and, finally, referential links between the two types of mental representations. According to Mayer, graphics support the understanding of a technical device under the following conditions: First, the learning material needs to contain information on cause and effect relations underlying the device. Second, the graphical presentations must show various system states and their interrelations. Third, the referential links between verbal and graphical information need to be supported by contiguity. Fourth, the learner is unfamiliar with the function of the device. These principles obviously apply both to graphics in written text and to animated graphics combined with auditory verbal explanations.

In chapter 9, Gyselinck and Tardieu investigate to what extent an already existing mental model may be further reinforced through the presentation of a related graphic. They describe an empirical study, in which an experimental group of subjects first read a text and then was given a graphical display. A control group read the same text twice. No substantial difference was found between the two groups concerning the course of learning. The authors conclude that a mental model needs to reach a certain degree of consolidation before it can be further elaborated with graphical information. Another interpretation could be that, in this case, readers construct a mental model from the text and that this model does not correspond well to the subsequently presented graphic. These discrepancies could have caused interference between the
graphic and the mental model. Accordingly, a possible conclusion could be that graphics should be presented from the beginning of a verbal description because this allows a learner to construct an outline of a mental model which can then be subsequently elaborated.

In chapter 10, Kulhavy, Stock and Caterino examine the conditions under which maps are an efficient aid for recalling text information. They assume that maps are encoded as intact images with a specific spatial structure. If such an image is in working memory, information contained in the map can be quickly located and used as a retrieval cue for the respective text information. According to the theory of conjoint processing developed by Kulhavy and his associates, maps increase the amount of information remembered when the maps are presented as organized visual displays, when subjects actually process the map, and when the text information to be remembered is directly related to the map. The authors raise the question whether the feature information and the structure information contained in a map contribute to the same extent to the retention of the respective text information. They demonstrate that feature information has no substantial effect on recall, whereas clear positive effects can be found for structure information. Accordingly, the mnemonical function of graphics is based upon their global structural characteristics and not upon their feature information.

**Differential and developmental aspects**

The topic in the third section is the influence of individual differences in prior knowledge and cognitive abilities, as well as developmental differences, on the comprehension of graphics. In chapter 11, McDaniel and Waddill examine how differences in reading ability modify the influence of graphics on recall of text information. A distinction is made between detail and relational information, essentially corresponding to the distinction between feature and structure information. McDaniel and Waddill discuss two views of the function of graphics, the first of which treats graphics as serving a compensatory function, i.e., that graphics help low ability readers. The second view treats graphics as serving an enrichment function, i.e., that graphics support high ability readers. According to the empirical findings of McDaniel and Waddill the compensating function of pictures seems to play a minor role, in that mainly high ability readers benefitted from graphics. High ability readers took advantage both of pictures presenting detail information and of pictures presenting relational information whereas low ability readers had higher recall of detail.

information only after having seen pictures with detail information. The authors conclude that graphical displays support encoding and retrieval of information, which is focussed on by the individual him/herself, as well as of information, which is difficult to encode only verbally. This applies, however, only if the individual has the necessary cognitive prerequisites. Therefore, both individual differences concerning the individual perspective of processing as well as differences concerning the cognitive abilities will affect the degree of success that individuals have comprehending graphics.

In chapter 12, Schnotz, Picard, and Henninger examine what factors make a difference that leads to deeper understanding of graphics and texts. The authors present a theoretical framework in which the comprehension of graphics is considered as a process of structure mapping between a graphic and an analog mental model. Accordingly, graphical entities are mapped onto mental entities and visuo-spatial relations are mapped onto semantical relations. The authors then report results from an empirical study which suggest that more successful learners interprete graphics more comprehensively, and, accordingly, achieve a more consistent mapping between the graphic and their mental model. The more successful learners also are more adapt in retrieving relevant text information at the right time. Finally, the authors discuss possibilities for improving graphics comprehension by giving students adequate processing strategies, such as aids for coordinating graphics and text information, and by selecting and sequencing learning tasks.

In chapter 13, Maichle examines differences exist between good and poor readers of line graphs. Using a thinking aloud method, she demonstrates that both good and poor graph readers are able to determine point values or single trends in a line graph. However, good graph readers do significantly better in extracting more complex, higher order information patterns. Furthermore, good graph readers invest more time and effort in orientation activities before extracting specific information from a line graph. These activities include informing themselves about the kind of information presented and about scale characteristics of the coordinate axes etc. Obviously, good graph readers use more elaborate graph schemata which enable them to parse a line graph in the appropriate way, to direct their attention to the relevant aspects and to transform perceptual patterns into the according semantical information. Poor graph readers, on the contrary, seem to possess only general graph schemata. Maichle discusses several implications of her results for the diagnosis of graph comprehension abilities and for the design of effective instructional programs to foster these abilities.
While the contribution of Maichle is concerned with understanding line graphs by adult learners, in chapter 14 Gobbo examines the kinds of problems that exist among younger subjects in the comprehension of line graphs. She demonstrates that learners of age 12 often have difficulties correctly understanding the interplay of the coordinate axes with the function curves being depicted. Furthermore, Gobbo points out that even adequately designed graphics do not insure greater understanding. Rather, the interpretation of a graphic can turn into a specific, cognitively demanding task and, as a result, the learner possesses fewer processing resources that can be directed to the learning of the instructional material. Obviously, in cases where people lack expertise with graphics, there is a trade-off between demands for processing the presentational form and demands for processing the actual instructional content.

In chapter 15 Gineste examines the effects of a pictorial presentation of analogies on the knowledge acquisition of young school-children. With reference to Piaget's concept of cognitive development, she demonstrates that a pictorial presentation significantly improves the understanding of analogies as compared with verbal presentation. Gineste concludes that a basic conceptual understanding of analogies has developed by this age, and that both the conceptual knowledge and the format in which analogies are presented are relevant factors for comprehension. Graphical presentation of analogies seems to facilitate the performance of younger school-children because it allows them to directly and visually depict the relevant semantic relations.

**Instructional aspects**

The last section addresses the instructional possibilities at graphics. In chapter 16, Seel and Dörr investigate whether the ability to spatially interpret technical drawings can be improved through special computer-based training programs. Starting out from Salomon's supplantation hypothesis, which postulates that mental processes can be supported through external simulation, Seel and Dörr have developed a training program in which the spatial projections in technical drawing are made manifest as shiftings and rotations with the help of a computer. The authors report an experiment in which learners using this training program performed better than learners using pure imagining instruction. Furthermore, Seel and Dörr found that it was easier for the subjects to transform three-dimensional objects into two-dimensional projections than vice versa. The results indicate that future
experiments on fostering graphic comprehension skills should take into account more explicitly the issue of encoding specificity and of learning transfer.

In chapter 17, Peeck analyses to what extent the instructional possibilities of graphics can be better employed by learners through providing them with explicit guidance for their cognitive processing. He discusses various possibilities, including: a simple invitation for the learner to look at a graphic, specific tips as to what part of a graphic should receive special attention, and tasks which require the learner to produce an external, controllable result. Based on his own studies, Peek concludes that learners are more successful when they are asked to identify what information from the text is being visualized with the graphic and how this is being accomplished. He points out, however, that learners are sometimes willing but not able to follow such instructions for the handling of texts and graphics. In particular, younger learners seem to need a lot of coaching before strategic training makes learning more efficient.

In chapter 18 Moore and Scevak examine whether improved comprehension of graphics and texts can be achieved when learners receive specific guidance about how to link text and graphic information. The authors report an experiment in which learners had to indicate after each text paragraph which part of a related tree diagram corresponded to the respective text paragraph. For these subjects the intensity of the linking and the learning result were positively correlated. On the whole, however, those subjects did not achieve as high levels of comprehension as subjects who received the text and the graphic without being asked to link them. The results indicate that positive consequences of employing certain processing strategies are possibly neutralized because these strategies require too much cognitive processing capacity. Too frequent mental switches from text information to graphic information and vice versa might, for example, interfere with global coherence formation. Moore and Scevak therefore emphasize the necessity of developing and teaching strategies that contribute to the construction of knowledge that is coherent both at the local and the global level.

In their concluding remarks, Schnotz and Kulhavy outline some general perspectives for future research. They conclude that the comprehension of graphics is a promising field for future research, in which cognitive psychology, educational psychology, semiotics, linguistics, and artificial intelligence can engage in a fruitful collaboration. Such research from different perspectives would provide a fairly good chance to attain a
A better theoretical understanding of graphics comprehension and a better basis for adequate practical decisions. A broader and deeper knowledge about this topic will become even more relevant in the future, when developments in multimedia, computer-based learning environments, and man-machine interfaces with strong emphasis on the visualization of information, will play ever larger roles in human life.

Wolfgang Schnotz

Raymond W. Kulhavy
Acknowledgements

The editors would like to thank a number of persons whose support contributed to the organization of the conference and to issuing this volume. We are very grateful to Steffen-Peter Ballstaedt, Helmut Felix Friedrich, Aemilian Hron, and Emmanuel Picard for their assistance in preparing and organizing the conference as well as to Christel Jansen, Hildegard Preißer and Margot Stoll for taking care of the various technical arrangements. Without their support, the meeting could not have been implemented successfully. We are also grateful to Claudia Petruch for the layout work on the completed manuscripts. Furthermore, we thank Michael Pfeiffer and Thomas Zink for supporting the work on the subject and author index. Our special thanks goes to the Volkswagen foundation which made this conference possible through its financial support.
This page intentionally left blank
List of Contributors

Linda C. Caterino
Walker Research Institute, 2441 East Edgewood Ave, Mesa, Arizona 85204 - 4601, USA

Michel Denis
Laboratoire d' Informatique pour la Mécanique et les Sciences de l'Ingénieur, Centre National de la Recherche Scientifique, PB 133, F-91403 Orsay Cedex, France

Günter Dörr
Pädagogische Hochschule Weingarten, Kirchplatz 2, D-88250 Weingarten, Germany

Johannes Engelkamp
Fachrichtung Psychologie im FB 6 der Universität des Saarlandes, Universitätscampus Bau 1.1, D-66123 Saarbrücken, Germany

August Fenk
Institut für Psychologie der Universität für Bildungswissenschaften Klagenfurt, Universitätsstraße 65-67, A-9022 Klagenfurt, Austria

Marie-Dominique Gineste
Laboratoire d' Informatique pour la Mécanique et les Sciences de l'Ingénieur, Centre National de la Recherche Scientifique, PB 133, F-91403 Orsay Cedex, France

Camilla Gobbo
University of Padova, Department of Psychology, Via B. Pellegrino 26, I-35137 Padova, Italy

Valérie Gyselinck
Laboratoire de Psychologie Cognitive de la Communication, Ecole Practique des Hautes Etudes, 3ème Section, 28 rue Serpente, F-75006 Paris, France
List of Contributors

Michael Henninger
Lehrstuhl für Empirische Pädagogik und Pädagogische Psychologie,
Universität München, Leopoldstraße 13, D-80802 München, Germany

John R. Kirby
Queen's University, Faculty of Education, Kingston Ontario, Canada
K7L 4L9, Canada

Raymond W. Kulhavy
Arizona State University, College of Education, Division of Psychology
in Education, Tempe, Arizona 85287-0611, USA

Abdellatif Laroui
Laboratoire d'Informatique pour la Mécanique et les Sciences de
l'Ingénieur, Centre National de la Recherche Scientifique,
PB 133, F-91403, Orsay Cedex, France

Ulla Maichle
Institut für Test- und Begabungsforschung der Studienstiftung des
deutschen Volkes, Koblenzer Straße 77, D-53177 Bonn, Germany

Richard E. Mayer
University of California, Department of Psychology, Santa Barbara CA
93106, USA

Mark A. McDaniel
Purdue University, 1346 Psychology Bldg., Room 3156, West Lafayette,
IN 47907-1364, USA

Gilbert Mohr
Fachrichtung Psychologie im FB 6 der Universität des Saarlandes,
Universitätscampus Bau 1.1, D-66123 Saarbrücken, Germany

Phillip J. Moore
University of Newcastle, Department of Education, Rankin Drive,
Shortland, Newcastle, NSW 2308, Australia

Joan Peeck
University of Utrecht, Department of Psychology, Heidelbergaan 2,
3584 CS Utrecht, The Netherlands