Impact of External Representation and Task on Graph Comprehension

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Abstract

This study examined the relationship between the external representation, verbal encoding vs. visual encoding, of graph information and the impact on graph comprehension. Graph comprehension tasks included responses to true/false statements addressing global and local graph information, visual recognition, and graph drawing. The findings suggest that the specific modality of the external representation play a role in the encoding and retrieval of some aspects of global vs. local graph information. The findings are discussed with reference to theories of spatial cognition.

Introduction

Numerical data is often externally represented in graphical visualizations to convey information that otherwise would be harder to extract from numbers presented in tables. The advantages of visual graphical presentations (such as bar, pie, line, charts) have been studied extensively (e.g., Meyer, Shinar, & Leiser, 1997). People, however, do not only look at graphs or data tables but also talk about them. Many tasks we perform with data graphs require the use of words to complete the task. For example, one may be asked to describe in words the annual trend in stock behavior of a certain company based on a graph. Or a mathematics teacher describes the graph she just drew on the blackboard to her students. Moreover, there is an increasing need to convey graph information also in verbal form. Examples include people with visual impairments who often need to utilize graph information, or people discussing graph information via online channels such as email, chats, or discussion boards, etc for training, education, or business purposes. The question is: what is the impact of such diverse external representations of numerical data, i.e., visual depictions vs. verbal descriptions, on graph information encoding and comprehension? The objective of the study reported here was to examine the impact of the external representation, graph and verbal description, on simple tasks of graph comprehension.

There is a growing need to present graph information in modalities other than the visual. One such need emerges from the community of people with a visual impairment. This major obstacle prevents the access to much information visualized graphically and it has been recognized and addressed (e.g., Brown, Brewster, Burton, Riedel, & Ramloll, 2003). Some of the more researched technological solutions include haptic or tactile displays (e.g., Challis & Edwards, 2001; Sjostrom, Danielson, Magnusson, & Rassmus-Grohn, 2003). Another approach is to use non-speech sounds or sonifications to convey the information expressed in visual graphs (e.g., Brown et.al, 2003; Flowers, Buhman, & Turnage, 1997). The growing need to present graph information in other modalities also emerges from the real and online, virtual world of communication, collaboration, training, and education (e.g., Pimm, 1987; Kramarski, 2002). This is particularly evident in teaching mathematics and the graphing of numerical information where there is a need to describe graphs in words. Taken together, such technological trends and research directions reflect the need to study the impact of various external representation of graph information and re-examine the current theoretical approaches to graph comprehension, particularly with respect to verbal encoding.

There are several commonly cited theories of graph comprehension (Carpenter & Shah, 1998; Freedman & Shah, 2002; Lohse, 1993; Pinker, 1990). Pinker (1990), for instance, suggests that a propositional representation is formed on the basis of a visual array constructed from the visual graph. Such a representation can trigger the appropriate graph schema which helps extract the required information from the graph. Similar to Pinker, Lohse (1993) also postulates the presence of a graph schema, although he never explicitly indicates if the representation is propositional. Freedman and Shah (2002) outline a model of graph comprehension that is based on the construction-integration theory of text comprehension. In the construction phase, the graph viewer perceives the visual features of the graph, including the peripheral information such as axes, labels and legends. During the integration phase, the visual features are comprehended based also on previous experience and domain knowledge, which is again reminiscent of Pinker's graph schema. It is interesting that the theories imply a propositional representation of graph information while primarily addressing the visual, pictorial external representation of graph information rather than verbal external representations of graphs.

There are very few studies looking at the verbal descriptions of graphs (e.g., Carswell, 1993; Carswell et.al., 1998; Shah, Hagerty, & Mayer, 1999; Katz, Xi, Kim, & Cheng, 2002). Katz et.al. (2002), for instance, proposed a theory of graph comprehension that also accounts for the aspects of communicating graph descriptions within the context of tests of spoken English. The main premise of their theory is the visual chunks hypothesis, where fewer visual chunks can lead to better verbal communication of graph information. However, even this approach did not address the issue of encoding graph information through a verbal, natural language description.

The main question of this research is: what is the impact of encoding graph information through verbal descriptions as compared to visual encoding? A follow-up question is: can any of the current theoretical approaches account for such potential impact? Some theoretical approaches suggest that graph cognition is associated with processes of spatial transformation (e.g., Trickett & Trafton, 2004; Webber & Feeney, 2002; Feeney & Webber, 2003). However, these studies did not extend or link their discussion to spatial cognition which may provide some new insights on graph cognition.

Similar to graphs, people can use words to describe the area they live in or what they learned from a map. People can also draw a map of an area they directly experienced or learned from a verbal description (e.g., Taylor & Tversky, 1992a, 1992b, 1996; Tversky and Lee, 1998). Such everyday anecdotes and research findings are indicative of our ability to encode, retrieve, and reason with spatial information both in image-based and verbal formats.

Based on such empirical similarities and theoretical links between graph and spatial cognition, we have adopted here the general experimental paradigm used in spatial cognition to examine the relationships between image-based and verbal information encoding. Tversky and Lee (1998) compared route descriptions (verbal) and route maps depictions (image-based) and found that both verbal descriptions and map drawings had a similar structure (e.g., starting and ending landmarks) and content. Tversky and Lee (1999) examined whether people can construct a meaningful whole verbal route description or route map depiction from limited spatial information given as either graphical depictions or verbal expressions. They found that participants did construct whole maps or verbal directions from the partial information given in each format. In the graph comprehension study reported here we also asked participants to encode graph information in different external representations and then tested their comprehension.

In addition, the approach adopted here is partially based on the experimental paradigm suggested by Feeney, Hola, Liversedge, Findlay and Metcalf (2000). They suggested an experimental paradigm in which participants need to indicate whether the information in a simple graph matched a verbal written description of the graph. The sentence-graph verification paradigm was appropriate here for examining the relationship between the verbal encoding vs. visual encoding of graph information.

Method

Participants

A total of 37 people participated in the study. This sample was divided into three groups; each performed a different graph comprehension task. There were 15 participants for a visual recognition task, 18 for a true-false questions task, and 10 for a graph drawing task. All participants were undergraduate students at Carleton University.

Study Design

Impact of graph external representation was tested as a within-participant factor. External representation of the graph information consisted of a visual presentation of a line graph (see example in figure 1), a written-verbal description of the graph, and a spoken-verbal description of the graph.

There were three graph cognition tasks each performed by a different group of participants to avoid carry-over effects and provide a within-participant comparison between the three external representations. Participants in group 1 responded to true/false statements about the graphs. The true/false statements consisted of two categories: global (overall pattern), and local (specific values). The global, overall pattern category included two statements: 1. Increase or decrease trends between certain x values (e.g., There is an increase between X2 and X3); 2. The relationships between two y values with respect to which is higher or lower, (e.g., the value at X3 is higher than the value at X5). The local, specific values category included two statements: 1. The y value for a specific x point (e.g., the value for X5 is 52); 2. The highest or lowest y value (e.g., the highest value is 97). Each graph was assigned four statements, one of each statement type.

Group 2 received a visual recognition task. The recognition task required the participant to view four line graphs, one of which was the test graph (presented in one of the three modes), and the other three served as distracters. Finally, group 3 received a graph drawing task. The task required participants to draw the graph from memory. The drawing was performed on a blank page.

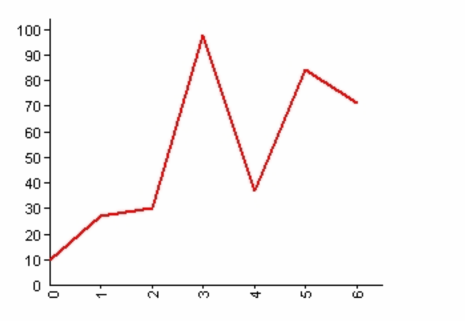

Figure 1: Example of a simple line graph used in this experiment.

Apparatus and Stimuli

The experimental stimuli were generated by a prototype application that automatically provides descriptions of graphs and allows for natural language interaction with a given graph (the inspectGraph system or iGraph). Input to the system comprised the encoding of the necessary properties of a graph in the EXtended Markup Language (XML) format (titles of the axes, values and the interval labels for the X-Axis). To allow for the description and the querying, our system implements the three following subsystems. The first takes the XML, parses it and writes a logic version of the given graph, together with several mathematical properties of the input graph (minimums and maximums, slope of the increase or decrease between two points, etc). The second subsystem stores different kinds of rules for describing and querying the logic-mathematical version of the input graph generated by the P-System. We call this the C-System. Third, the language subsystem takes the logic-like representations (and, in principle, all possible inferences) from the rest and second subsystems and outputs a natural language text (both as a description and/or as the response to a query) plus the handling of a dialogue modeling algorithm for querying the graph. We call this the L-System.

The following verbal description was generated by inspectGraph for the line graph presented in figure 1: "The graph starts at 10 at x0. There is an increase at x1 to 27. There is an increase at x2 to 30. There is an increase at x3 to 98. There is a decrease at x4 to 37. There is an increase at x5 to 84. Finally, there is a decrease at x6 to 71". Note that at present, the verbal output includes a straightforward description of each point and its relationship to the preceding neighboring point. This verbal description can either be presented as text or be synthesized into a spoken description.

A total of 36 different line graphs were generated. The 36 graphs were divided into the three external representations: 12 graphs presented as a visual depiction, 12 as a written description displayed on the test monitor, and 12 as a spoken description.

Procedure

Participants were randomly assigned to one of the three graph cognition tasks. Each participant was presented with all 36 graphs. The order of graph presentations in any one of the three external representations was randomized across participants.

Participants started with the first presentation, viewing a graph, reading a graph description, or listening to a graph description. After each graph presentation, participants completed the relevant task, then went on to the next graph, completed the task, and so on until all 36 graphs had been presented. Exposure times for the three presentation modes were X and were determined by preliminary pilot trials with a few users. It should be emphasized that the graph depiction or verbal description were not available to participants while performing the task.

Results

True/False Questions

Correct Responses The mean number of correct responses was computed for each of the four statements (two global and two local) as a function of the external representation. A two-way ANOVA with repeated measures (3 modalities by 4 statements) was performed to test the impact of external representation and statement. There was a significant interaction ($F_{6,102}$=7.1, p=0.00) between the two variables. Since similar patterns were found for both statements in each category, an overall mean correct number of responses was calculated for each category. An additional two-way ANOVA with repeated-measures (3 modalities by 2 categories) was performed to test the impact of external representation and statement category and it also yielded a significant interaction ($F_{2,34}$= 22.5, p=0.00). This interaction is shown in figure 2.

The largest differences between the two statement categories, global and local, were found for the visual encoding condition. Post hoc comparisons showed that the mean number of correct responses to statements in the overall pattern category was higher than responses to the specific values category when graph information was encoded from a visual graph. Such large difference was not found when encoding was based on verbal description, visual or spoken.

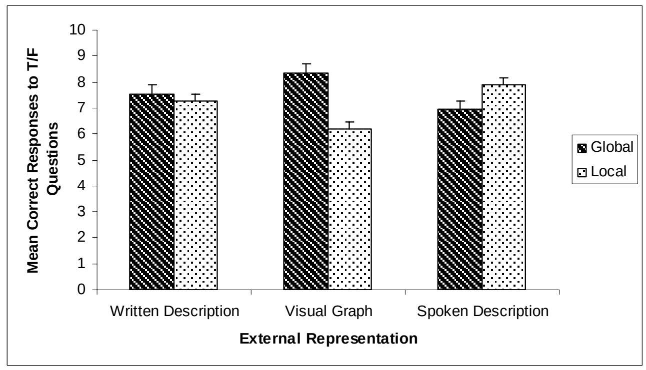

Figure 2: Mean number of correct responses to true/false questions by question category as a function of encoding modalities.

Response Times Mean response times for each of the four statements were computed as a function of external representation. A two-way ANOVA with repeated measures (3 modalities by 4 statements) was performed to test the impact of external representation and statements on response times. The interaction was significant ($F_{6,102}$=3.7, p=0.01). Since similar patterns were found for both statements in each category, an overall mean correct response was calculated for each category and an additional two-way ANOVA with repeated measures (3 modalities by 2 categories) was performed to test the impact of external representation and statement category. This interaction was also significant ($F_{2,34}$= 7.5, p=0.003) as can be seen in figure 3.

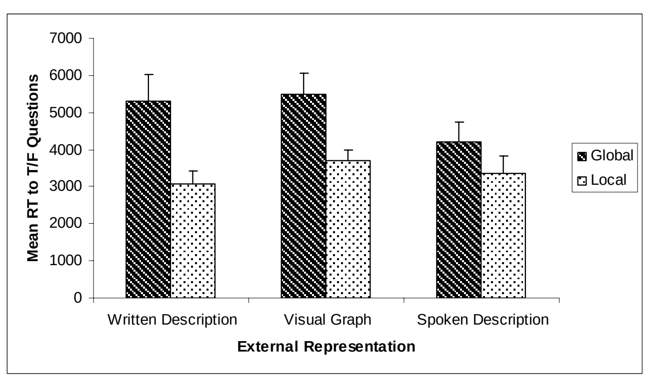

Figure 3: Mean times in ms to respond to true/false questions by question category as a function of encoding modalities.

The figure shows that mean response times for the statements in the global category were longer than response time to local statements for all three encoding modalities. Post-hoc comparisons showed that response times for the spoken graphs did not differ for the two statement categories whereas it did for the visual and textual modes.

Drawing

Two indices were computed to reflect goodness of graph drawing. Index 1, number of correctly drawn inter-point trends, increase or decrease (with a maximum of six correct trends in the graphs used here). Index 2, number of correctly drawn highest and lowest points (with a maximum of two in the graphs used here). Due to a technical problem in encoding the data from the written description encoding condition, only the visual graph and spoken description conditions were analyzed.

Paired-samples Student t-tests were performed to test the impact of encoding modality on the two map drawing goodness indices. A significant difference was found for index 2. When encoding was based on the visual graph, the mean number of correct drawings of the highest and lowest points (mean = 1, SE = 0.11) was higher than the spoken description encoding (mean = 0.7, SE = 0.10). No significant difference was found between the two modalities for the number of correctly drawn inter-point trends.

Visual Recognition

The mean number of correct responses was computed for the visual recognition tests for each of the three encoding modalities. A one-way ANOVA with repeated measures performed to test the impact of encoding modality on success in the recognition task resulted in a significant main effect ($F_{2,28}$= 4.6, $p<0.05$). The mean number of correct recognition responses was highest for the visual encoding condition (mean = 11, SE=0.2) as compared with the written description encoding (mean= 9.7, SE= 0.6) and the spoken description (mean = 9.6, SE= 0.5).

The one-way ANOVA computed for the mean recognition response times in the three encoding conditions was significant ($F_{2,28}$= 40.4, $p=0.00$). Response times were shorter for the visual encoding condition (mean = 6627ms, SE=566) than for the written description encoding (mean= 13407ms, SE= 947) and the spoken description (mean = 14528ms, SE= 1060).

Discussion

Summary of Findings

Generally, the findings here show that people can encode graph information from a verbal description in natural language. A verbal description, either written or spoken, was associated with graph comprehension performance that occasionally was equivalent to the performance with visual encoding.

When graph information was encoded visually or in written verbal descriptions, durations of graph comprehension performance were significantly different between global and local aspects. It took significantly longer to respond to true/false statements addressing global information (i.e., overall trends) compared to responding to statements on local information (specific values) in the test graphs. These findings are generally in line with previous research suggesting that it is more difficult and takes longer to answer questions on global information than on local information (e.g., Ratwani, Trafton, and Boehm-Davies 2003).

In addition, when encoding was based on a visual graph, there were significantly more correct responses to the global-information questions than to the local information questions. No such differences were found when encoding was based on the verbal written or spoken descriptions. It should be emphasized that mean number of correct responses to local information was significantly lower in the visual graph encoding condition than in the written and spoken verbal encoding conditions.

The impact of the external representation was also found with one part of the drawing task. Correctly drawing the highest and lowest points in the graph was significantly better in the visual graph encoding condition than in the spoken verbal description condition. No differences were found between the visual graph encoding and the spoken verbal description in drawing all the inter-point trends. While inter-point trends can be viewed as global graph information, the lack of difference between the two modalities can be accounted for by the fact that the verbal descriptions included explicit trend information such as: “There is an increase at x2 to 30”. Finally, the visual graph encoding was associated with the best performance in the straightforward task of visual recognition of the test graph. The superior performance was observed with both the number of correct responses and with a shorter response time of the recognition.

Taken together, the findings here reflect a relationship between the external representation of graph information and graph comprehension performance. More specifically, the particular modality of the external representation seems to play a role in the encoding and retrieval of some aspects of global vs. local graph information.

Theoretical Implications

Impact of external representation What are the theoretical implications of the ability to encode and comprehend graphs, both verbally and image-based? The findings here reveal two aspects in graph comprehension as a function of the external representation. One, visual graph encoding leads to better performance with global graph information whereas verbal descriptions are less sensitive to differences between global and local information. This is indirectly in line with findings comparing tables and graphs (e.g., Meyer et.al., 1997) where graphs have an advantage when the task requires comprehension of relationships and trends (global features here) as opposed to specific values (local features here). The second aspect is the possible speed-accuracy tradeoff associated with visual encoding conditions. The findings here suggest that while it may take longer to answer questions on global aspects, the responses are more accurate when graph information was encoded visually. Can this imply that graph information encoded visually may be internally represented differently from verbal encoding? As will be discussed in the next paragraph, such implication is not supported by some of the theoretical approaches in spatial cognition.

Paivio (1969, 1991) suggested the dual-coding theory addressing the way in which visual and non-visual information is encoded and represented. Dual-coding theory suggests that memory consists of two separate but inter-related codings and representations, verbal and visual. The inter-connections allow for dual-coding of information received in one modality. In spatial cognition, Tversky (1991) and Cohen (1996) suggested that mental models of the environment are based on analogue visuo-spatial codes and abstract propositional codes. Tversky and Lee (1999) postulated a possible automatic translation between the mechanisms encoding verbal and image-based types of spatial information (also, Franklin, 1992). Earlier on, Jackendoff (1987), Jackendoff and Landau (1991), and Bryant (1992) have made a general argument that perceptual and linguistic inputs of spatial information are initially analyzed by separate systems through various levels of representation, modality-specific encoding and representation, and then translated into a common representation that is modality independent (empirical evidence reviewed in Bryant, 1992). Further studies of the speed-accuracy tradeoff found here are needed to assess whether in graph cognition there is a modality-specific encoding and representation.

Global vs. local information Ratwani et.al., (2003) claimed that few graph comprehension theories address various aspects of graph comprehension tasks. Specifically, they claimed that the theories do not address and account for performance with global vs. local aspects of graph information. However, this problem can be viewed from a different perspective. Freedman and Shah's model (2002) suggests that both top-down (e.g., graph skills, domain knowledge) and bottom up (perception of visual features) processes are involved in graph comprehension. The co-presence of such processes has been addressed in perception and cognition, and is often expressed in the contrast between feature extraction and integration theories, on the one hand, and the more structuralist, Gestalt theories of perception and attention, on the other hand. Earlier studies implied the precedence of top-down processing by demonstrating the global precedence phenomena in perception (Navon, 1981; Pomrantz, 1981). Extending the analog to findings of spatial cognition, the precedence of global vs. local landmark impact on spatial cognition was shown previously (e.g., Steck & Mallot, 2000). It is possible that with image-based encoding there is more global feature precedence, which is similar in perceiving global graph features or landmarks in one's environment. In other words, verbal information tends to be more detailed and elaborate, thus providing more local, specific value-oriented information. The image-based information tends to convey the more general trends and relationships in the information (e.g., Meyer et.al. 1997).

Summary While there is no conclusive evidence in the spatial cognition literature to support any one specific theoretical approach, some similarities can be drawn to graph comprehension. Graph information can be encoded by separate mechanisms and then translated into a common internal representation that is modality independent. More research is needed to examine the possible theoretical link between graph comprehension and spatial cognition. In the study reported here we demonstrated that the cross-modality comparison in graph information encoding can provide some new insights as to the internal cognitive process of graph comprehension.

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References

Brown, L.M., Brewster, S.A., Burto9n, M., Riedel, B. and Ramloll, R. (2003). Design guidelines for audio presentation of graphs and tables. In the Proceedings of the 2003 International Conference of Auditory Display. Boston, MA, USA, July 6-9, 2003.

Bryant, D.J. (1992). A spatial representation system in humans. Psycholoquy, 3, #16 Space (1).

Carpenter, P. A., and Shah, P.A. (1998). A model of the perceptual and conceptual processes in graph comprehension. Journal of Experimental Psychology: Applied, 4, 75-100.

Carswell, C.M. (1993). Stimulus complexity and information integration in the spontaneous interpretations of line graphs. Applied Cognitive Psychology, 7, 341-357.

Carswell, C.M., Bates, J.R., Pregliasco, N.R., Lonon, A., and Urban, J. (1998). Finding graphs useful: Linking preference to performance for one cognitive tool. International Journal of Cognitive Technology, 3, 4-18.

Challis, B, and Edwards, A.D.N. (2001). Design principles for tactile interaction. in Haptic Human-Computer Interaction (LNCS 2058), S. A. Brewster and R. Murray-Smith, Eds. Berlin, Germany: Springer.

Cohen, G. (1996). Memory in the real world. 2nd Edition. Hove: Psychology Press.

Feeney, A., Hola A.K.W., Liversedge, S.P., Findlay, J.M., and Metcalf, R. (2000). How people extract information from graphs: Evidence from a sentence-graph verification paradigm. In M. Anderson, P. Cheng, and V. Haarslev (Eds.): Diagrams 2000, LNAI 1889, pp. 149-16.

Feeney, A. & Webber, L. J. Analogical representation and graph comprehension. Lecture Notes in Computer Science Vol. 2733 (2003) 212-221.

Flowers, J., Buhman, D., Turnage, K. (1997). Cross-modal equivalence of visual and auditory scatterplots for exploring bivariate data samples. Human Factors 39(3) 341.

Franklin, N. (1992). Spatial representation for described environments. Geoforum, 23 (2), 165-174.

Freedman, E.G., and Shah, P. (2002). Toward a model of knowledge-based graph comprehension. In M. Hegarty, B. Meyer, and N. Hari Narayanan (Eds.): Diagrams 2002, LNAI 2317, pp. 18–30.

Jackendoff, R. (1987). Consciousness and the computational mind. Cambridge, MA: MIT Press.

Jackendoff, R. & Landau, B. (1991). Spatial language and spatial cognition. In D. J. Napoli & J. A. Kegl (Eds.), Bridges between psychology and linguistics: A Swarthmore festschrift for Lila Gleitman. Hillsdale, NJ: Lawrence Erlbaum Associates.

Katz, I. R., Xi, X., Kim, H.-J., & Cheng, P. C. H. (2002). Graph Structure Supports Graph Description. In W. Gray & C. Schunn (Eds.), Proceedings of the Twenty Fourth Annual Conference of the Cognitive Science Society (pp. 530-535). Mahwah, NJ: Lawrence Erbaum.

Klatzky, R.L., Lippa, Y., Loomis, J.M., & Golledge, R.G. (2003). Encoding, learning, and spatial updating of multiple object locations specified by 3-D sound, spatial language, and vision. Exp. Brain Res., 149, 48-61.

Kramarski, B. (2002). Enhancing mathematical discourse: The effects of e-mail conversation on learning graphing. In the proceedings of the International Council for Education Media Annual Conference, Taipei, pp. 101-106.

Lohse, G.L. (1993). A cognitive model for understanding graphical perception. Human Computer Interaction, 8, 353-388.

Mevarech, ZR and Kramarski, B (1997b) From verbal descriptions to graphic representations: misconceptions regarding the construction of linear graphs, Educational Studies in Mathematics, 32, 229–263.

Meyer, J., Shinar, D., & Leiser, D. (1997). Multiple factors that determine performance with tables and graphs. Human Factors, 39/2, 268–286.

Navon, D. (1981). The forest revisited: More on global precedence. Psychological Resrach, 43, 1-32.

Paivio, A. (1969). Mental imagery in associative learning and memory. Psychological Review, 76, 241-263.

Paivio, A. (1991). Dual coding theory: retrospect and current status. Canadian Journal of Psychology 45, 255-87.

Pimm, D. (1987). Speaking Mathematically: Communication Mathematics Classroom, Routledge & Kegan Paul, London.

Pinker, S. (1990). A theory of graph comprehension. In R. Freedle (Ed.), Artificial Intelligence and the Future of Testing. Mahwah, NJ: Earlbaum.

Pomerantz, J.R. (1981). Perceptual organization in information processing. In M. Kubovy and J.R. Pomerantz, (Eds.), Perceptual organization (pp. 141-180). Hillsdale, NJ: Erlbaum.

Ratwani, R. M., Trafton, J. G., & Boehm-Davis, D. A. (2003). Thinking graphically: Extracting local and global information. In R. Alterman & D. Kirsch (Eds.), *Proceedings of the 25th Annual Meeting of the Cognitive Science Society*, Boston, MA.

Shah, P., Hagerty, M., and Mayer, R.E. (1999). Graphs as aids to knowledge construction: Signaling techniques for guiding the process of graph comprehension. Language Testing, 16, 399-425.

Sjosrom, C., Danielsson, H., Magnusson, C., and Rassmus-Grohn, K. (2003). Phantom-based haptic line graphics for blind persons. Visual Impairment Research. 5 (1), 13-32.

Steck, S.D., & Mallot, H.A., (2000). The role of global and local landmarks in virtual environment navigation. *Presence, 9 (1),* 69–83

Taylor, H.A. and Tversky, B. (1992a). Descriptions and Depictions of Environments, *Memory and Cognition* 20(5): 483–496.

Taylor, H.A. and Tversky, B. (1992b). Spatial Mental Models Derived from Survey and Route Descriptions, *Journal of Memory and Language* 31: 261–292.

Taylor, H.A. and Tversky, B. (1996). Perspective in spatial descriptions, *Journal of Memory and Language* 35, 371–391.

Taylor, H.A., Uttal, D.H., Fisher, J., & Mazepa, M. (2001). Ambiguity in acquiring spatial representations from descriptions compared to depictions: The role of spatial orientation. In D.R. Montello (Ed.): COSIT, LNCS 2205, pp. 278-291.

Trickett, S.B., and Trafton, G. (2004). Spatial transformation in graph comprehension. In Blackwell et.al. (Eds.): Diagram 2004, Springer_verlag Berlin Heidelberg, pp. 372-375.

Tversky, B. (1991). Spatial Mental Models. *Psychology of Learning and Motivation Advances in Research and Theory, 27*, 109-145.

Tversky, B., Kim, J., & Cohen, A. (1999). Mental models of spatial relations and transformations from language. In C. Habel & G. Rickheit (Eds.): Mental models in discourse processing and reasoning. Pp. 239-258, Amsterdam: North-Holland.

Tversky, B. (2003a). Structures of Mental Spaces; How people think about space. *Environment and Behavior, 35*, 66-80.

Tversky, B. & Lee, P.U. (1998). How space structures language. In C. Freska, C. Habel, & K.F. Wender (eds.), Spatial Cognition: An interdisciplinary approach to representation and processing of spatial knowledge, pp. 157-175. Berlin: Springer-Verlag.

Tversky, B. & Lee, P.U. (1999). Pictorial and verbal tools for conveying routes. In C. Freksa, D.M. Mark (Eds.): Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science: International Conference COSIT'99, Stade, Germany, August 1999. Pp. 51.

Webber, L. J. & Feeney, A. How people represent and reason from graphs. In Proceedings of the 25th Annual Conference of the Cognitive Science Society. Mahwah, NJ: LEA (2003) 1206-1211.