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Speed of Comprehension of Visualized Ordered Sets

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The authors investigated the effects of visual properties of hierarchical graphs on speed of comprehension: planarity (crossing of lines), slopes (orientation of lines), and levels (adjustment of dots). In each of 4 experiments, 30 participants responded to interpretive questions that required comparisons among the elements of the graph. Knowledge provided to participants differed across Experiments 1a, 1b, and 1c; question demands varied in Experiment 2. Analysis of response latencies showed that crossing of lines is the most influential variable independent of orientation, dot adjustment, and question demands. Speed of comprehension decreased with increasing question demands. When question demands were high, orientation of lines also had an effect on speed of comprehension. Preliminary conclusions for the presentation of hierarchical graphs are drawn.

Psychological research on graph comprehension has concentrated on the comprehension of visualized numerical, especially statistical, data (see Lewandowsky & Spence, 1989); for the presentation of such data, textbooks are available (e.g., Cleveland, 1993, 1994; Kosslyn, 1994; Tukey, 1977). However, there is a lack of research on conceptual graphs (Butler, 1993), which represent relations among nonnumerical entities or concepts. The helpfulness of such graphs and diagrams has often been reported when readers have to learn from texts (e.g., Guri-Rozenblit, 1988; Hegarty & Just, 1993; Mayer & Gallini, 1990; Sweller, Chandler, Tierney, & Cooper, 1990). Educators in mathematics have pointed out how important it is that students learn how to produce diagrams from texts, as well as how to interpret such diagrams (e.g., Barwise & Etchemendy, 1991; Goldin, 1985; Lewis, 1989). In this article, we deal with a special type of conceptual graph, that is, hierarchical graphs (see Figure 1 for an example). The data underlying such graphs can be described by so-called ordered sets. Aside from their widespread use in engineering, science, and everyday life, the need for psychological research on graphs of nonnumerical data is all the more obvious since Novick and Hmelo (1994) and Novick, Hurley, and Francis (1999) emphasized the important role of such graphs and diagrams in problem solving and thinking.

A considerable amount of research devoted to visualization of nonnumerical data has been carried out by specialists, such as computer scientists and mathematicians. They appreciate the properties of ordered sets for the graphical presentation of ordered information, such as the structure of computer file systems, hierarchical information as shown in Figure 1, preference information, and many other sorts of ordered data.

Kosslyn (1989) presented an analytic scheme in which the interrelations of basic graphic constituents can be analyzed with respect to syntactic, semantic, and pragmatic levels. Syntactic-level analysis focuses on the entities of lines and regions of a graph without interpreting them in terms of what they represent. Semantic analysis concentrates on the literal meanings of the configuration of lines and components of a graph, their relations, and what they represent. Analysis on the pragmatic level refers to information conveyed by meaningful symbols that transcends the direct semantic interpretation.

For each level of analysis, Kosslyn (1989) derived acceptability principles based on general psychological findings pertaining to visual processing, the Gestalt laws, and so on. Reduced or erroneous comprehension of graphs may arise from violations of those principles. In the discussion of our results, we interpret the impact of visual properties on speed of comprehension with respect to Kosslyn's acceptability principles.

In this article, we investigated the speed of comprehending nonnumerical, visually presented data, specifically, ordered sets represented by hierarchical graphs as shown in Figure 1. Speed is one of the most important and common variables in graph comprehension research. It is especially relevant to hierarchical graphs when considering the extensive use of graphical file browsers. Latency measurement is frequently used to assess the efficiency of comprehension. For example, Hollands and Spence (1998) and Spence (1990) used judgments of proportion and their latencies to assess accuracy and speed of comprehension for various graphical representations of numerical data. In order to assess the speed of comprehension, Rinck and Glowalla (1994) measured reaction times for answers to questions on graphs.

In the following, we briefly introduce ordered sets and their visualizations as hierarchical graphs: so-called upward drawings. We introduce three special properties of upward drawings, which we denote as visual properties. These properties are derived from corresponding mathematical properties of ordered sets (Rival, 1993): *Visual planarity* refers to whether lines in the drawing are

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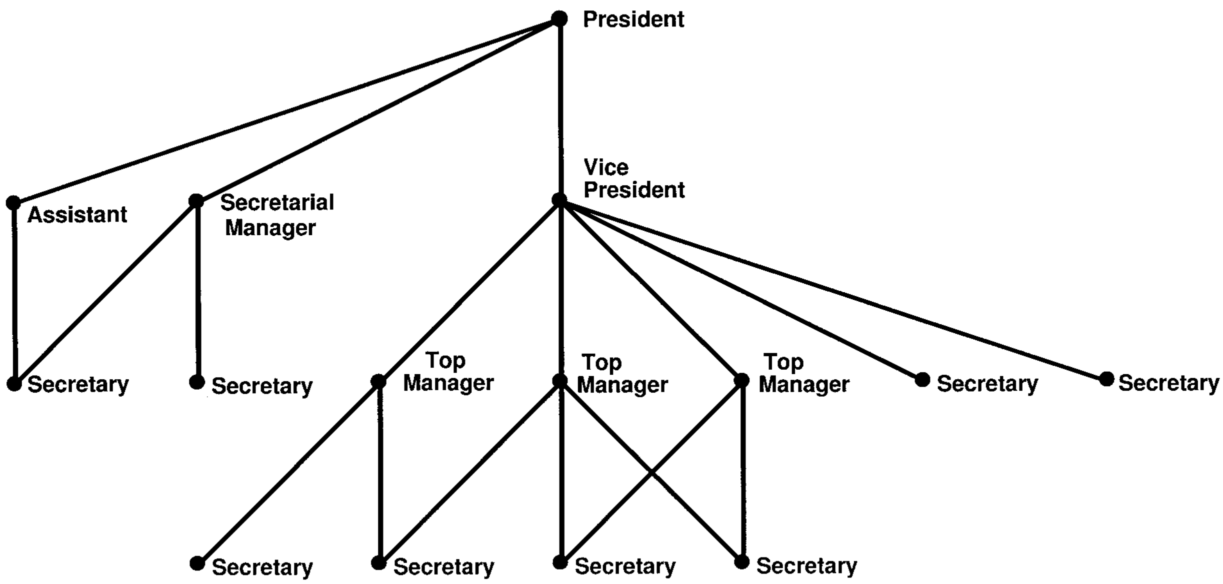

Figure 1. Example of a visualization of the superior relation of a firm.

crossed, *visual slopes* refers to the orientation of lines, and *visual levels* refers to the adjustment of dots or circles in the drawing. The visual properties serve as main independent variables in our experiments, and we define attributes for the properties, which serve as the levels of these variables. Upward drawings are not unique; that is, the same data can be represented by different drawings. Therefore, visual properties are heavily used to achieve more comprehensible upward drawings, which makes psychological investigations of such properties all the more essential. In our experiments, we tested the effects of the visual properties of planarity, slopes, and levels on the speed of comprehension. We interpret our results in terms of psychological findings and identify additional variables that may control comprehension speed.

Upward Drawings and Their Visual Properties

Figure 1 shows a hierarchy of superiority relations for a group of people (managers, secretaries, assistants) working in a firm. The superior relation among all the individuals in the firm, from the president on down, is an example of an ordered set, and Figure 1 is a visualization (upward drawing) of this set.

The superior relation is regarded as a relation between pairs of elements (objects or individuals); that is, the relation is binary. A binary relation that is irreflexive and transitive is called a (strict partially) *ordered set.* For example, the vice president is superior to top managers, but not to himself or herself (irreflexivity). Because the president is superior to the vice president, who is in turn superior to the top managers, the president is also superior to the top managers (transitivity). Many more sorts of ordered sets (e.g., partial orders, weak orders) can be visualized with upward drawings (see e.g., Davey & Priestley, 1990).

An upward drawing of an ordered set is accomplished by drawing a labeled dot or circle for each element of the set and a line connecting the dots if this pair is in the specified relation. (Instead of a label along the side of a dot, only the label can be drawn.) A line is drawn only between *neighboring* dots, and omitted for all other dots. The superordinate object is drawn vertically above a subordinate one (*directedness*). The omission of transitive lines prevents the drawing from becoming crowded with connecting lines. The transitive nature of the ordered set ensures that the reader can infer the ordering of all pairs in the relation.

The visualization in Figure 1 illustrates the advantages of upward drawings. The structure of the ordered elements is readily apparent. It is presented more distinctly than in the form of a list that enumerates all the pairs of elements in the specified relation. Moreover, the omission of transitive lines simplifies the appearance of the drawing.

Not all possible pairs of individuals in the firm are comparable with respect to the hierarchical relation (*comparability*). For example, the assistant to the president is superior to a secretary, but not to the top managers. Such pairs of elements are called *incomparable.*

For the proper interpretation of the information contained in upward drawings, a reader needs knowledge of directedness, (in) comparability, and neighboring. In our experiments, we imparted the respective knowledge to participants. Planarity is the most widely discussed property regarding the visualization of ordered sets (Rival, 1993). For *visual planarity* we define the following attributes: The upward drawing of an ordered set is considered *noncrossed* (p_1) if, and only if, no line crossings occur; otherwise, it is considered *crossed* (p_2). Not every ordered set can be drawn noncrossed. However, the remainder can be drawn crossed or noncrossed. For example, in Figure 2 the same ordered set is drawn with crossings (left, right) and without crossings (middle).

Slopes refer to the number of differentially slanted lines in a drawing needed to represent the neighboring relations. The maximum number of slopes in a drawing is realized if each line is drawn with a different slope. The minimum number of slopes needed in a drawing is usually much lower than the maximum number. The drawings in Figure 2 (left and right) use three slopes, whereas the middle drawing in Figure 2 includes the maximum of

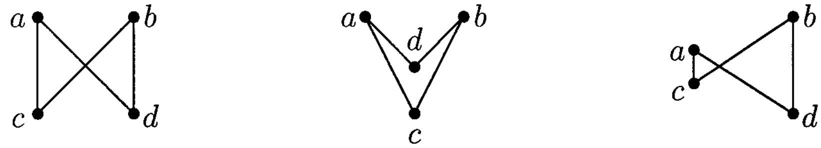

Figure 2. Three alternative upward drawings for the same ordered set.

four slopes. For visual slopes we call an upward drawing of an ordered set *upright* (s_1) if, and only if, it is drawn with as few slopes as possible; otherwise, it is called *slanted* (s_2). A small number of slopes is a desirable attribute of drawings. For example, the mathematicians Czyzowicz, Pelc, and Rival (1990, p. 234) wrote that "it is an everyday inclination common to all, who have experienced the preparation of many such diagrams for display, to minimize the actual number of slopes needed."

It may be desirable to have upward drawings in which all neighboring elements of each element are collected as dots on the same horizontal level (Pelc & Rival, 1991). Not every ordered set can be drawn that way, it depends on the mathematical properties of the set. However, the remainder can be drawn with neighboring elements as dots on the same line or not. For example, in Figure 2 (left) the dots of neighboring elements are collected on a horizontal level for each element. In the drawings of Figure 2 (middle and right) this is not the case. For *visual levels* we consider an upward drawing of an ordered set to be *horizontal* (l_1) if, and only if, all dots representing neighbors of an element are drawn at the same height; otherwise, it is called *nonhorizontal* (l_2).

The combination of the three dichotomous visual properties yields eight types of drawings. We denote each type by specifying its attributes in the form (p_i, s_j, l_k) indicating which of the two respective attributes is present.

Figure 3 shows eight upward drawings of an ordered set with 9 dots and 10 lines representing the following pairs of ordered elements: (*a, b*), (*a, c*), (*a, d*), (*b, f*), (*c, g*), (*d, g*), (*e, g*), (*e, h*), (*g, i*), and (*h, i*), as well as the pairs (*a, f*), (*a, g*), (*a, i*), (*c, i*), (*d, i*), and (*e, i*) inferred by transitivity. These upward drawings were actually used in our experiments. Type (p_1, s_1, l_1) in Figure 3 shows the upward drawing that incorporates all of the desired attributes; that is, it is noncrossed, upright, and horizontal. Type (p_2, s_2, l_2) shows the same ordered set in the crossed, slanted, and nonhorizontal representation.

From the examples in Figure 3, it is obvious that basic psychological principles of perception apply, such as grouping and configuration principles and the Gestalt laws (see e.g., Pomerantz & Kubovy, 1986). For example, the crossed lines of drawing (p_2, s_2, l_2) might be salient properties that draw attention and distract the visual system from the message of the drawing. Also, crossed drawings may involve several superimposed, irregularly shaped polygons. The contour of these polygons may guide a reader's eye, thus leading to task-irrelevant information in the graph. Generally, line crossings may make it difficult to discriminate interconnections among dots and slow down comprehension.

Furthermore, the most important feature of upward drawings is their directedness. It exploits human vision by using perceptual properties to convey the conceptual relation of superiority. It is best visualized by means of vertical lines. A variety of slopes, however, will deteriorate fast discrimination of slanted drawings compared with drawings with a small number of distinct slopes.

Finally, horizontally adjusted dots may create the impression of a line (Gestalt law of good continuation), and thus emphasize the relatedness of elements that are neighbors of another element. The resulting upward drawings might also conform to the Gestalt

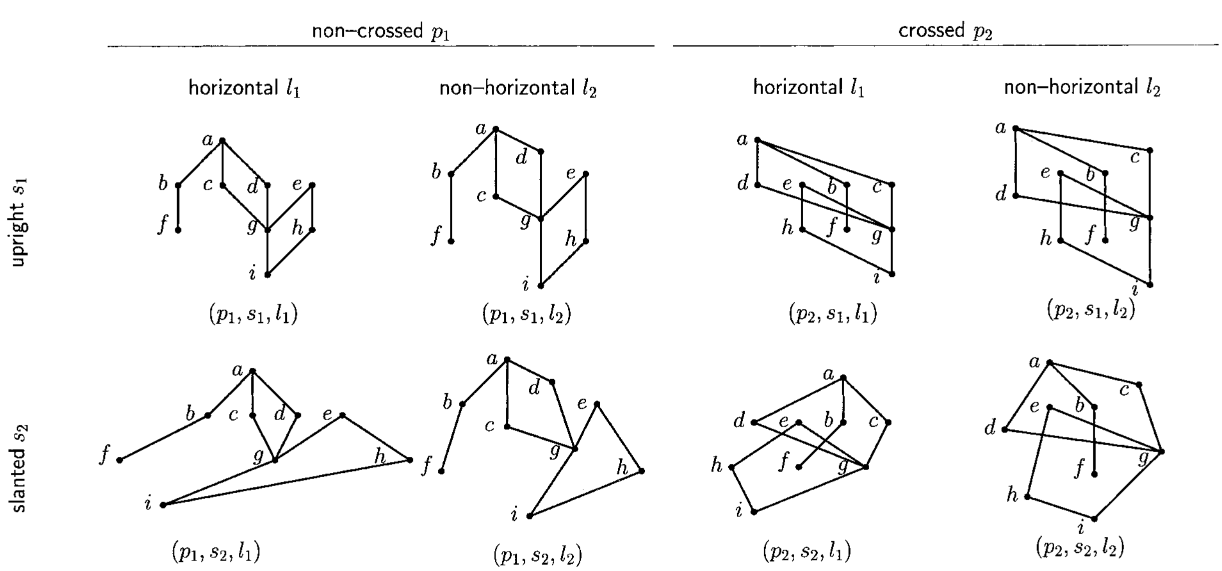

Figure 3. Upward drawings used in experiments, visualizing the same ordered set.

principle of good form and can be expected to facilitate comprehension.

Experiments 1a, 1b, and 1c

The visual properties imply simple psychological hypotheses. We expect faster comprehension of visualized ordered sets for noncrossed upward drawings, compared with crossed drawings. It is faster for upright, compared with slanted drawings, and is faster for horizontal, compared with nonhorizontal drawings.

However, the mathematicians Kisielewicz and Rival (1993, p. 2) among others, stated that "the first and foremost criterion for a 'good' drawing is 'planarity.' " Indeed, visual planarity may be a major variable that produces upward drawings with a good form. We, therefore, expect that visual planarity may have a stronger influence on speed of comprehension than the other properties.

In Experiments 1a, 1b, and 1c we focused on the influence of visual properties. Our hypotheses on visual properties were inspired by the experience of experts in the field. Indeed, Maichle (1994) and Shah and Carpenter (1995) found performance differences between graph readers with different levels of experience. However, we expected that visual properties matter not only to experts but also to less experienced readers. Therefore, the knowledge of upward drawings was varied among experiments. We expected that the impact of visual properties is, by and large, independent of the available knowledge; that is, we anticipated the same effects for all experiments. Specifically, we predicted effects of visual properties even for readers who had minimal knowledge about upward drawings.

To test our predictions, we investigated effects of visual properties on response latencies. Participants answered simple questions concerning information represented in upward drawings. The three experiments were identical except that participants were given varying amounts of knowledge of ordered sets. In consideration of this knowledge, respective questions were posed in each experiment (control questions). For reasons of comparability among the experiments, we analyzed only data pertaining to questions that were identical in all experiments (identical questions).

Method

Participants in the three experiments worked on problems by answering questions regarding an ordered set represented by upward drawings. These drawings represented the eight drawing types obtained from combining the attributes of the visual properties. The ordered information was presented to participants in the context of preferences of hypothetical persons for various cities as vacation destinations. Preferences among a set of choice alternatives with several aspects or dimensions lead to a (strict) partial order on the set of alternatives (Roberts, 1979). Participants were given different amounts of knowledge of ordered sets in the experiments. Responses and response latencies to the questions were recorded. Because design and procedure of the three experiments are similar, we report them together.

Design

In each of the experiments, the properties of visual planarity, visual slopes, and visual levels were varied in a $2 \times 2 \times 2$ factorial design with repeated measures on all variables. Visual planarity, slopes, and levels varied on two levels: An upward drawing could be either noncrossed (p_1) or crossed (p_2), upright (s_1) or slanted (s_2), horizontal (l_1) or nonhorizontal (l_2).

Participants in Experiment 1a were instructed about upward drawings (directedness, comparability, neighboring). In Experiment 1b, instructions were limited to directedness and comparability. In Experiment 1c, only knowledge of directedness was imparted.

Participants

Ninety students at the University of Graz (30 in each experiment) participated. Mathematics students were excluded in order to control for prior knowledge of ordered sets. Participants in Experiment 1a were psychology students who received class credit; the average age was 21.5 years (range = 18–40).

Participants in Experiments 1b and 1c were paid ($7.50/hr). The average age was 23.5 years (range = 18–36) in Experiment 1b; the average age in Experiment 1c was 27.1 years (range = 18–41).

Materials

The combination of 8 upward drawings with 20 questions yielded 160 problems (question–drawing combinations). These problems were presented to participants in each experiment.

Upward drawings. For the experiments, we selected an ordered set with 9 elements and 16 pairs. Eight upward drawings were constructed from this basic ordered set. Each drawing represented one of the eight types resulting from the combination of the three dichotomous visual properties. The drawings differed only with respect to their visual properties, but not with respect to the represented ordered set (see Figure 3).

Because the participants' task (see below) consisted of interpreting the vacation preferences of hypothetical people, names of nine European capital cities were assigned to elements *a* through *i* of the ordered set when presented to participants (see Figure 4). In each drawing, these labels were always drawn to the left of the circle symbolizing that city. For the practice part of each experiment, we used an upward drawing of a less complex ordered set.

Questions. The 20 questions consisted of 10 questions used in each experiment (identical questions), and 10 questions used to control for the specifically instructed knowledge in each experiment (control questions). The 10 identical questions referred only to directedness; that is, they could be verified by comparing the vertical position of dots without knowledge of comparability or neighboring. Participants verified the assertion of a question by responding "yes" or "no" accordingly.

The question with a correct answer being "yes" was constructed by selecting a city and a distinct number of cities for comparison, for example, "Does this person like to travel to London, Rome, and Lisbon more than to Vienna?" The corresponding no question was constructed by interchanging cities, for example, "Does this person like to travel to Vienna, Rome, and Lisbon more than to London?" The number of elements to be compared varied from one to three. Questions were phrased in two ways: "Does this person like to travel to London, Rome, and Lisbon more than to Vienna?" (right-phrased), or "Does this person like to travel to Rome more than to Madrid, Berlin, and Stockholm?" (left-phrased).

In order to cope with possible response strategies in repeatedly answering the same questions, the 10 identical questions varied with respect to (a) the correct answer (solution) to a question, (b) the number of cities to be compared, and (c) the phrasing of a question. The questions were grouped together into five pairs. Within a pair of questions, only the correct answer was varied; number of compared cities and phrasing varied across question pairs. Table 1 gives an overview of the construction scheme.

The 10 control questions were also grouped together into five pairs. The control questions from Experiments 1b and 1c were similar to the questions that were identical across all experiments. Control questions differed across experiments and, therefore, they are not comparable across experiments,

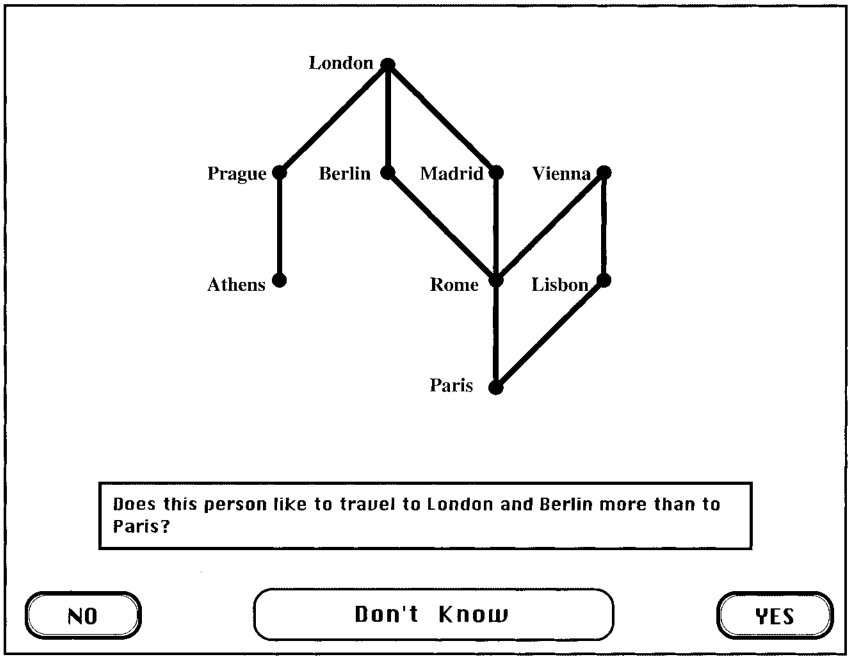

Figure 4. Layout of the screen showing an upward drawing, a question, and an assignment of the response keys.

which is why we restrict data analysis to identical questions (discussed later).

Apparatus

Drawings and questions were displayed on a 14-inch (36-cm) diagonal computer monitor. The leftmost and rightmost keys in the same row as the space bar were used for yes or no responses, respectively. These two keys were assigned randomly to the type of response (yes or no) in order to cope with participants' handedness. The space bar was used for a "don't know" answer. The viewing distance was approximately 60 cm.

Table 1
Experiments 1a, 1b, and 1c: Construction Scheme of Questions Identical Across Experiments

Question pair	Question	Solution	Compared cities	Phrasing
1				
	1	yes	2	right
	2	no		
2				
	3	yes	1	
	4	no		
3				
	5	yes	3	left
	6	no		
4				
	7	yes	3	right
	8	no		
5				
	9	yes	2	left
	10	no		

Note. Phrasing for Question Pair 2 is identical because only one element is compared. Ordering of the question pairs corresponded to the presentation sequence.

Task and Instruction

The purpose of the written instructions was to familiarize participants with upward drawings as a means of visualizing preference information. Two examples of upward drawings illustrating preferences of hypothetical persons for vacation cities were discussed in detail. Participants were told that they would have to answer questions concerning several drawings that illustrated vacation preferences.

We provided varying degrees of knowledge in the three experiments. In the instruction for Experiment 1a, we explained directedness, comparability, and neighboring. In the instruction for Experiment 1b, directedness and comparability were explained. In the instruction for Experiment 1c, only directedness was explained. Directedness, comparability, and neighboring were defined and illustrated in detail by respective examples. Thus, all knowledge relevant for answering the questions was imparted, although knowledge of directedness was sufficient for correctly answering the identical questions.

Participants were told that the questions would be very simple, so that they would be able to answer rapidly by pressing the appropriate response key ("yes" or "no"). To diminish guessing, participants were instructed to press the space bar if they did not know the answer.

Procedure

After reading the written instructions, participants practiced on 20 problems obtained from the combination of the practice drawing (see previous descriptions) with 20 practice questions similar to the questions described previously. Thus, they could familiarize themselves with the labeling in the drawings and the response procedure. Feedback on the correctness of each response was displayed. At the beginning of the main part, participants returned the instructions to the experimenter. They were informed that feedback would no longer be available.

The presentation of a problem (question–drawing combination) constituted one trial. The participant started a trial by pressing the space bar. At the beginning of each trial, the question and the assignment of the response keys for the current trial were displayed. Participants were instructed first to read the question and to determine the key assignment. (This was done in order to minimize the additional time necessary for the decision about which key to press.)

As soon as the participant pressed the space bar again, the word "Attention!" (in German) was presented for 1,000 ms in the middle of the screen, followed by an upward drawing. The question and key assignment remained visible during the presentation of the drawing (see Figure 4).

As soon as the participant pressed a response key, the screen was cleared and a request to start the next trial was presented. Thus, the trials were self-paced. The computer recorded the response and its latency by timing the interval from presentation of the drawing until the participant's key press. The participant worked through all problems in this way.

The two identical questions forming a pair (see Table 1), combined with each of the eight drawings, constituted 1 block of 16 trials each. Thus, the 80 problems with identical questions were divided into 5 blocks. The same was done with the 80 problems involving control questions. The sequence of trials within a block was randomized for each participant. The sequence of the blocks was identical for all participants and corresponded to the sequence of question pairs in Table 1. The five blocks of control questions were interposed after Block 1 (2 blocks), Block 3 (1 block), and Block 5 (2 blocks).

Results and Discussion

We report results for the three experiments in the form *aaa*/*bbb*/*ccc,* where *aaa* denote values for Experiment 1a and *bbb* and *ccc* denote values for Experiments 1b and 1c, respectively. After reporting the percentages of correct responses, we report results from the latency analysis. The analysis is restricted to questions identical across experiments. Control questions differed among experiments; in Experiments 1b and 1c they were similar to the identical questions. As a consequence, the latencies obtained from these experiments are smaller due to practice. Therefore, we do not conduct direct comparisons of the absolute magnitude of latencies among experiments but concentrate on the pattern of results.

We obtained a total of 2,400/2,400/2,400 responses and associated response latencies for the 30 participants and 80 problems in each experiment; 5/3/3 responses were excluded because keys other than the indicated response keys had been pressed on the keyboard. A response to a question was coded correct if the appropriate answer (yes or no) was given. There were 6/1/2 don't know responses that were coded as incorrect. The low frequency shows that participants generally felt certain about their answers.

The success of instruction and practice is documented by 2,321/2,337/2,341 (96.9%/97.6%/97.7%) correct responses (solutions). Having established the intended effect of instruction and practice, we limit subsequent analyses to latencies of correct responses.

The focus of the latency analyses was on medians. The median response latency per drawing was computed for each participant across the 10 questions. These individual medians were averaged across participants; that is, we calculated the arithmetic mean for each drawing on the basis of the respective medians of the 30 participants in an experiment. The overall mean of the median latencies was 7.33/5.77/5.17 s (*SD*s = 0.58/0.39/0.37 s). In Figure 5, the latency differences between the two levels of each factor are depicted (latency for graphs with an undesired attribute minus latency for graphs with a desired attribute). The differences are all in the expected direction (i.e., positive).

A 2 × 2 × 2 factorial analysis of variance (ANOVA) with repeated measures on all variables and the median latencies as dependent measures yielded a main effect of visual planarity in all experiments. Effects for visual slopes or levels were not significant

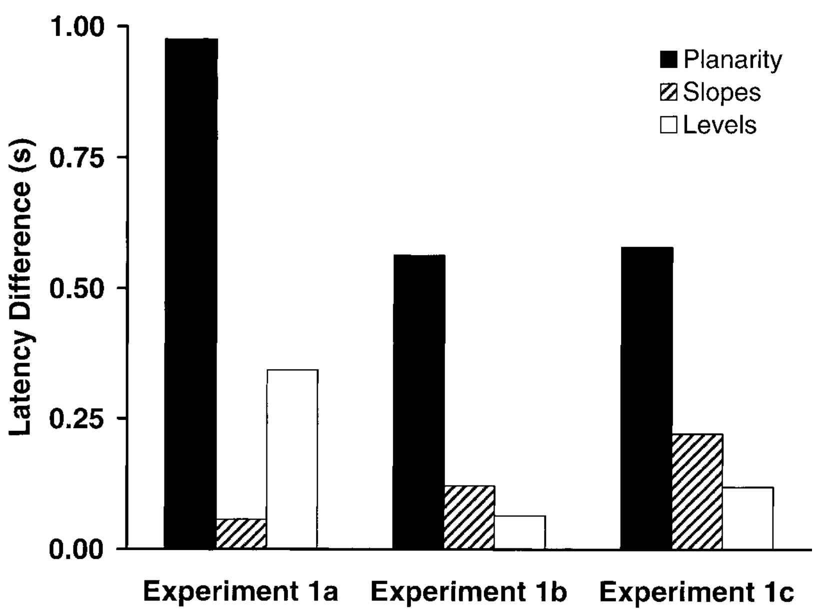

Figure 5. Experiments 1a–1c: Latency differences between attributes of visual properties separated for experiments.

in any experiment. Only one interaction of visual planarity by visual levels for Experiment 1b was found (see Table 2).

In the preceding analysis, yes and no questions were pooled. However, visual properties may have different effects for yes and no questions. Therefore, we repeated the analysis separately for those kinds of questions by partitioning the data into latencies obtained from yes questions and no questions. We report the results on a summary level only. For yes questions, there was a pronounced effect of planarity in all experiments ($p < .01/p < .01/p < .01$), which was, by and large, also found for no questions ($p < .01/p < .05/p > .05$). Moreover, we found an effect for visual levels in Experiments 1a ($p < .01$) and 1b ($p < .01$) for yes questions and an interaction for visual planarity and levels in Experiment 1b for no questions ($p < .05$). As these results are based on only five or fewer (correct) responses per participant, we rely on the results of the pooled data for the interpretation and postpone further investigation of questions to Experiment 2.

The analyses confirm the assumption that visual planarity is a major property of upward drawings, as predicted. In fact, the results seem to indicate that it is the only important variable. Moreover, planarity seems to exert its effect on both yes and no questions. This pattern of results was found throughout all experiments.

Noncrossed upward drawings facilitate comprehension the most. The strong influence of planarity is impressive if one considers that the questions answered by the participants were simple (i.e., the required number of comparisons among elements was small). The limited effect of visual properties other than planarity might be increased if the information to be obtained from upward drawings was more demanding. To test this possibility, we examined the effect of visual properties in Experiment 2 by using more demanding questions.

Experiment 2

The questions used in Experiments 1a, 1b, and 1c were very simple. Participants had to verify whether an element of the ordered set was in the ordering relation compared with, at most, three other elements of the set. Consequently, this task required a maximum of three comparisons among the elements. The limited effect of visual properties other than planarity may be due to the simplicity of the questions used. Experiment 2 was designed to investigate the effect of visual properties on speed of comprehension when the number of elements to be compared was systematically varied.

We assumed that whenever the number of comparisons for a question was increased, speed of comprehension would decrease compared with questions that required fewer comparisons. We used differently phrased questions that required two to six comparisons.

Moreover, we also considered the difference between yes and no questions. In order to approve the assertion implied by a yes question, participants needed to compare one element with all the other elements. No questions could be denied as soon as an element was found that was not in the requested relation. We expected that participants would not use an exhaustive comparison strategy in the case of no questions. Therefore, the decrease in speed of comprehension should be smaller for no questions compared with yes questions when the number of comparisons was increased.

Finally, by increasing the number of comparisons we expected visual properties to have a stronger effect on the speed of comprehension compared with Experiments 1a, 1b, and 1c: The more demanding the questions became, the more planarity, as well as slopes and levels, would affect speed of comprehension.

Method

In a procedure identical to that used in Experiments 1a, 1b, and 1c, except for the randomization of trials, participants answered questions about hypothetical persons' vacation preferences, which varied in regard to the number of comparisons. We used the same eight drawings as in Experiments 1a, 1b, and 1c that varied with respect to visual planarity, slopes, and levels. We imparted knowledge pertaining to directedness and comparability as in Experiment 1b. The questions were designed to investigate the effects of the number of comparisons necessary to answer questions, and the effects of approval (yes question) and denial (no question) of a question. We recorded participants' responses and their latencies for answering the questions.

Participants

A total of 31 first-semester psychology students at the University of Graz participated in Experiment 2 for class credit. The average age

Table 2
Experiment 1a, 1b, and 1c: Analysis of Variance for Visual Properties

		Experiment 1a		Experiment 1b		Experiment 1c	
Source	*df*	*F*	*f*	*F*	*f*	*F*	*f*
Planarity (P)	1	26.52**	0.91	33.02**	1.14	15.88**	0.55
Slopes (S)	1	0.13	0.00	1.25	0.04	2.08	0.07
Levels (L)	1	4.04	0.14	0.14	0.01	1.30	0.05
P × S	1	2.39	0.08	0.00	0.00	0.67	0.02
P × L	1	0.23	0.01	6.54*	0.23	2.57	0.09
S × L	1	1.24	0.04	0.10	0.00	0.52	0.02
P × S × L	1	1.01	0.04	0.59	0.02	3.19	0.11
P × Sub. within-group error	29	(2.15)		(0.78)		(1.27)	

Note. All reported statistics are within subjects. Values enclosed in parentheses represent mean square errors. f = Cohen's f; Sub. = subjects.
* $p < .05$. ** $p < .01$.

was 23.9 years (range = 18–57). One participant was excluded from the analysis because his or her mean response latency (25.48 s) differed substantially from the mean response latency (11.93 s) of the other participants.

Design

The visual properties of planarity, slopes, and levels, as well as the number of comparisons necessary for the verification of questions were varied in a 2 × 2 × 2 × 5 factorial design with repeated measures on all variables. Visual planarity, slopes, and levels varied on two levels: An upward drawing could be either noncrossed (p_1) or crossed (p_2), upright (s_1) or slanted (s_2), or horizontal (l_1) or nonhorizontal (l_2). The number of comparisons varied from a minimum of two to a maximum of six.

Materials

We used the same eight upward drawings varying with respect to visual planarity, slopes, and levels in Experiment 2 as in the previous experiments (see Figure 3). Twenty-six new questions were constructed. Drawings and questions were completely crossed, resulting in 208 problems for the experiment.

The 26 verification questions were subdivided into two types. The 20 questions of the first type (single-comparison questions) were similar to the questions in Experiments 1a, 1b, and 1c. A single element was compared with some other elements, for example, “Does this person like to travel to London and Lisbon more than to Rome?”

Within the second type of six questions, two elements were compared with some other elements (double-comparison question). As an example, consider the following yes question: “Does this person like to travel to Lisbon, Rome, and Vienna more than to London, but less than to Berlin?” Verification of such a question required six comparisons.

The 26 questions were grouped into 13 pairs. The pairs were constructed with respect to (a) the solution to a question, (b) the number of cities to be compared, and (c) the phrasing of a question. Within a pair of questions, only the correct answer was varied. Phrasing varied only across single-comparison questions; the number of cities to be compared varied across both types of questions.

Single-comparison yes questions were constructed by selecting an element and two to six other comparable elements for comparison. The corresponding no questions were constructed by randomly replacing one of the elements to be compared with an incomparable one. As in Experiments 1a, 1b, and 1c, single-comparison questions could be left-phrased or right-phrased.

The yes and no double-comparison questions were constructed similarly, except that the phrasing did not vary and the number of cities to be compared varied from one to three. Table 3 gives an overview of the question construction scheme. To approve the assertion implied by a yes question, a participant had to compare two to six cities with one city in single-comparison questions, yielding two to six comparisons. For double-comparison questions the participant had to compare two to three cities with two cities in double-comparison questions yielding two, four, and six comparisons. For denial of a no question, such an exhaustive comparison was, in principle, not necessary. Comparisons could be stopped as soon as a city was found to be incomparable with the requested one (or two other) cities.

Task, Instruction, and Procedure

We used the same instruction as in Experiment 1b; that is, we defined and illustrated directedness and comparability through detailed examples. Except for small changes in the randomization of trials (see below), the procedure was identical to the procedure used in Experiments 1a, 1b, and 1c. The identical apparatus was used. Again, an experimental session consisted of an extensive instructional and practice part, followed by the main part.

In the instruction and practice part, participants read written instructions and practiced on the 20 practice problems used in Experiment 1b; feedback followed for each response. In the main part, participants worked on the 208 problems of this experiment without feedback; problems were presented in random order for each participant.

Table 3
Experiment 2: Construction Scheme of (Single- and Double-Comparison) Questions

Question pair	Question	No. of comparisons	Solution	Compared cities	Phrasing
1					
	1	6	yes	6	single/left
	2		no		
2					
	3	6	yes	6	single/right
	4		no		
3					
	5	5	yes	5	single/left
	6		no		
4					
	7	5	yes	5	single/right
	8		no		
5					
	9	4	yes	4	single/left
	10		no		
6					
	11	4	yes	4	single/right
	12		no		
7					
	13	3	yes	3	single/left
	14		no		
8					
	15	3	yes	3	single/right
	16		no		
9					
	17	2	yes	2	single/left
	18		no		
10					
	19	2	yes	2	single/right
	20		no		
11					
	21	6	yes	3	double
	22		no		
12					
	23	4	yes	2	double
	24		no		
13					
	25	2	yes	1	double
	26		no		

Note. Questions 1–20 were single-comparison questions; questions 21–26 were double-comparison questions.

Results and Discussion

For the 30 participants, data from 208 problems yielded a total of 6,240 responses and associated response latencies. A response was coded correct if the participant gave the appropriate answer (yes or no); there were 18 don’t know responses that were coded as incorrect.

The success of instruction and practice was documented by 5,851 (93.9%) correct responses. In the analyses to follow, only correct responses were considered. As in the previous experiments, the focus of the latency analyses was on medians. The mean of the median latencies for the eight graphs was 10.64 s ($SD = 0.84$ s). Table 4 provides the mean median latencies for visual properties.

A 2 × 2 × 2 factorial ANOVA with repeated measures on the visual properties and the median latencies as dependent measures (taken from yes and no questions) yielded a main effect of visual planarity and a main effect of visual slopes (see Table 5).

For examining possibly different influences of yes versus no questions, we carried out the same analysis separately for those questions. For yes questions, we also found main effects of planarity and slopes, but for no questions only planarity was significant, as well as an interaction between slopes and levels (see Table 5). The latency differences between the levels of the visual properties are given separately in Figure 6 for all questions, and for yes and no questions.

A 2 × 5 factorial ANOVA with repeated measures on the type of questions (yes vs. no) and the number of comparisons showed that the approval of yes questions generally needed 1.38 s longer, on average, than the denial of no questions, $F(1, 29) = 19.10$, $MSE = 7.43$, $f = 0.66$, $p < .01$, as expected. The response latencies increased with the number of comparisons needed to answer a question, $F(4, 116) = 163.26$, $MSE = 2.81$, $f = 5.62$, $p < .01$. As predicted, the increase was more pronounced for yes questions compared with no questions, which is why the interaction was also significant, $F(4, 116) = 21.90$, $MSE = 1.55$, $f = 0.75$, $p < .01$. Figure 7 provides the mean latencies for yes and no questions and number of comparisons. We regressed the number of comparisons on the latencies of all questions to ensure that this increase was systematic, ($R^2 = .27$, $b = 1.36$, $\beta = .52$, $p < .01$).

The next analysis is devoted to the predicted interaction of visual properties and number of comparisons. We expected that the influence of visual properties might increase as the questions become more demanding; that is, the number of required comparisons increases. A 2 × 2 × 2 × 5 factorial ANOVA with repeated measures on all variables and the median latencies as dependent measures revealed effects for visual planarity and visual slopes, as well as for the number of comparisons. The interaction of planarity with the number of comparisons was significant, the interaction of slopes with the number of comparisons was not. We found no other effects (see Table 6). Figure 8 presents the latency differences for the visual properties for each number of comparisons.

The same analysis conducted separately for yes and no questions showed that the reported effects are mainly due to yes questions, as expected. For yes questions, we found strong effects for visual planarity and slopes, as well as for the number of comparisons. There were also strong interaction effects for planarity with the number of comparisons and slopes with the number of comparisons. For no questions, we obtained only effects of planarity and the number of comparisons (see Table 6). To ensure that the observed effects of planarity and slopes increased systematically with the number of comparisons, we tested yes questions involving two and three comparisons (low number of comparisons) against yes questions involving five and six comparisons (high number of comparisons) in noncrossed versus crossed drawings (planarity); the same was done with upright versus slanted drawings (slopes). The latency difference of 6.28 s between low and high number of comparisons for noncrossed drawings was substantially smaller than the difference of 7.72 s for crossed drawings, which is why all the effects in Table 7 are significant. The same was true for the variable slopes. This systematic sort of interaction is illustrated in Figure 9.

With respect to the effect of visual properties, the results of Experiment 2 replicated the strong effect obtained for visual planarity, which was again found to have the strongest influence on speed of comprehension and produced the largest latency difference. Regardless of the solution to a question, noncrossed upward drawings considerably facilitated speed of comprehension. Moreover, visual slopes also substantially facilitated comprehension in this experiment.

In sum, visual properties, as expected, were shown to have a much stronger influence on the speed of comprehension in Experiment 2 compared with the previous experiments. This can be indirectly inferred from the result that visual planarity and slopes had a stronger effect for questions with five and six comparisons compared with only two and three comparisons (the number of comparisons prevailing in Experiments 1a, 1b, and 1c).

The participants in Experiment 2 had to answer questions that were more demanding than those in Experiments 1a, 1b, and 1c. On average, the questions required more comparisons among elements of the ordered set. The data analysis showed that the speed of comprehension systematically decreases as the number of comparisons among the elements of an ordered set increases. It can be reasonably assumed that the increased impact of visual properties observed in Experiment 2 is due to the more demanding questions. This result emphasizes that the impact of visual properties increases as the information to be obtained from a drawing becomes more demanding; that is, more comparisons are required (see above).

Taken together, the various results contribute to a quite uniform picture. The visual properties of planarity and slopes both facilitate

Table 4
Experiment 2: Mean Median Latencies (in Seconds) and Standard Deviations for Visual Properties and Questions

	Planarity				Slopes				Levels			
	Noncrossed		Crossed		Upright		Slanted		Horizontal		Nonhorizontal	
Questions	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
All questions	9.90	0.50	11.37	0.56	10.41	0.54	10.87	0.52	10.60	0.51	10.70	0.55
Yes questions	10.81	0.52	12.23	0.55	11.13	0.52	11.91	0.54	11.48	0.51	11.60	0.55
No questions	9.20	0.51	10.76	0.61	9.80	0.60	10.16	0.51	9.90	0.55	10.06	0.56

Table 5
Experiment 2: Analysis of Variance for Visual Properties and Varying Types of Questions

Source	*df*	All questions		Yes questions		No questions	
		F	*f*	*F*	*f*	*F*	*f*
Planarity (P)	1	65.54**	2.26	53.54**	1.85	30.88**	1.06
Slopes (S)	1	7.68*	0.27	15.86**	0.55	2.49	0.09
Levels (L)	1	0.26	0.01	0.20	0.01	0.46	0.06
P × S	1	0.01	0.00	1.23	0.04	0.00	0.00
P × L	1	3.07	0.11	0.18	0.01	0.69	0.02
S × L	1	0.51	0.02	0.46	0.02	5.14*	0.18
P × S × L	1	0.58	0.02	0.56	0.02	0.00	0.00
P × Sub. within-group error	29	(1.98)		(2.25)		(4.70)	

Note. All reported statistics are within subjects. Values enclosed in parentheses represent mean square errors. *f* = Cohen's *f;* Sub. = subjects.
* $p < .05$. ** $p < .01$.

comprehension speed. The effects of these properties increase as the questions become more demanding, and are due rather to yes questions than to no questions. However, visual planarity exerts such a strong influence that it is decisive, no matter how simple or demanding a question or the solution to it is.

General Discussion

The four experiments demonstrated a strong influence of visual properties on speed of comprehension of visualized ordered sets. In each experiment, visual planarity had the strongest effect; in Experiment 2, visual slopes also had a substantial effect (see Figures 5 and 6). The impact of visual properties further increases if the information to be extracted from the drawings is more demanding. This was evident in Experiment 2 where the questions demanded, on average, more comparisons among elements of the ordered set.

Our hypotheses were derived from an analysis of visual properties originating from the extensive experience of mathematicians and computer scientists. Our results show that visual properties do not just matter to experts. Even readers with relatively little instruction and training profit from the desirable attributes (Experiment 1c). The same influence of visual properties was found for participants equipped with differing levels of relevant knowledge. The influence of the visual properties is independent of participants' other knowledge of ordered sets. Moreover, Experiments 1a, 1b, and 1c show that visual properties, especially planarity, facilitate comprehension even when quite simple information must be obtained from a drawing, and more so in the case of more demanding information (Experiment 2).

Considering the effect of planarity, it is not clear what specific property of crossed drawings is responsible for the latency disadvantage. Is it the general disarrangement of lines and dots present

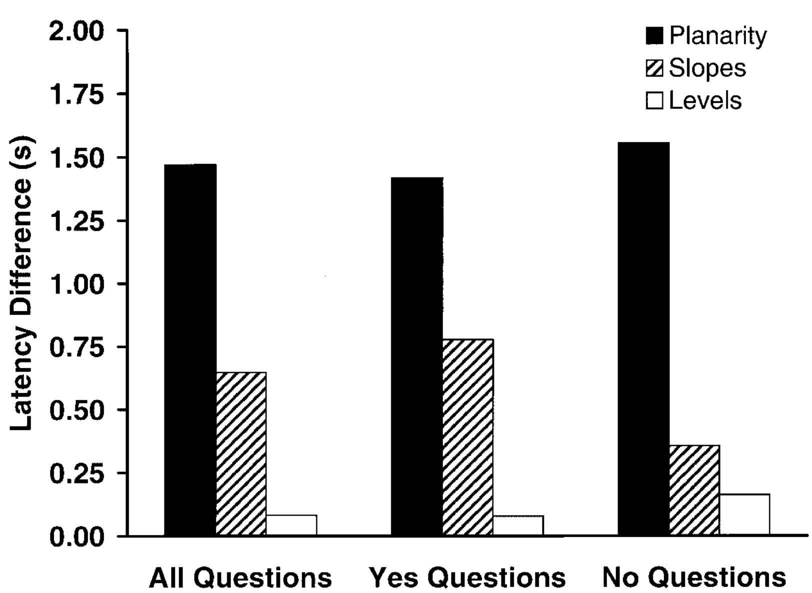

Figure 6. Experiment 2: Latency differences between attributes of visual properties separated for all questions and yes and no questions.

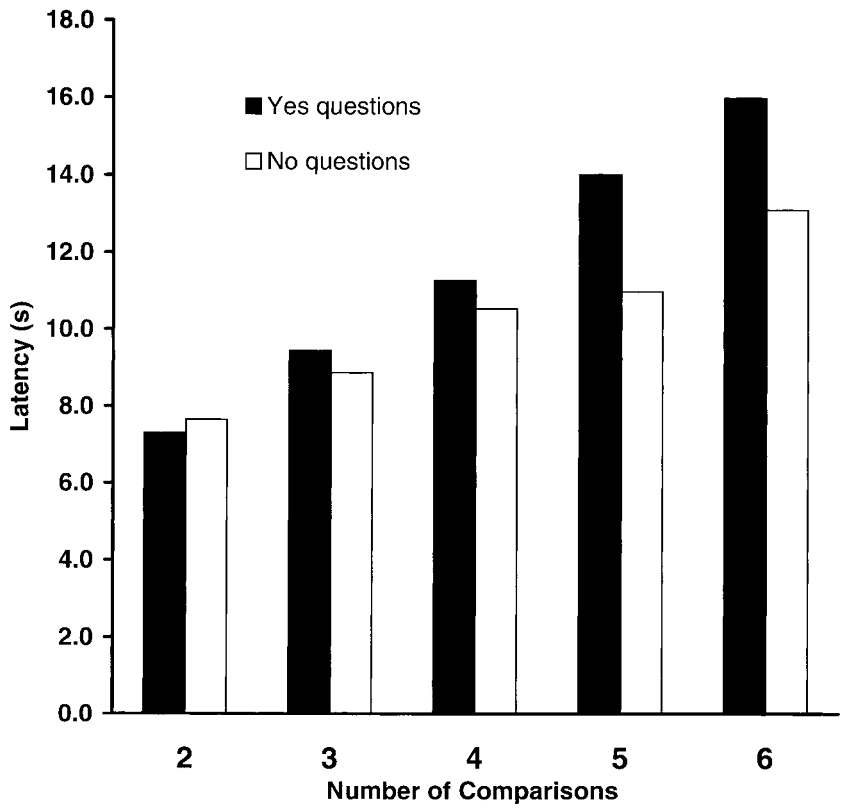

Figure 7. Experiment 2: Response latencies for number of comparisons separated for "yes" and "no" questions.

in crossed drawings, or the fact that specific lines may be crossed by other lines when a reader follows those lines? For example, consider a question involving elements *d*, *g*, and *i* (see Figure 3). When answering such a question in a crossed drawing, the reader's eye may follow the line between *d* and *g* when he or she encounters the crossing caused by the line connecting elements *b* and *f*. The reader's eyes could also follow that line upward in the direction of element *b*, which would result in a delayed identification of

Table 6
Experiment 2: Analysis of Variance for Visual Properties and Number of Comparisons

		All questions		Yes questions		No questions	
Source	*df*	*F*	*f*	*F*	*f*	*F*	*f*
Planarity (P)	1	84.75**	2.92	123.73**	4.26	36.05**	1.24
Slopes (S)	1	8.66*	0.30	15.70**	0.54	0.01	0.00
Levels (L)	1	3.28	0.11	1.01	0.04	2.88	0.10
Comparisons (C)	4	180.17**	6.19	217.81**	7.47	71.84**	2.47
P × S	1	1.62	0.06	1.61	0.06	0.65	0.02
P × L	1	0.47	0.02	0.06	0.00	0.58	0.02
P × C	4	5.19**	0.18	6.28**	0.22	1.51	0.05
S × L	1	0.01	0.00	1.57	0.05	0.70	0.03
S × C	4	1.55	0.05	3.78**	0.13	1.24	0.04
L × C	4	1.86	0.06	1.96	0.07	1.44	0.05
P × S × L	4	1.27	0.04	0.30	0.01	0.78	0.03
P × S × C	4	2.07	0.07	0.39	0.01	0.28	0.01
P × L × C	4	1.32	0.05	0.67	0.02	0.53	0.02
S × L × C	4	0.52	0.02	0.15	0.01	0.41	0.01
P × S × L × C	4	2.18	0.08	2.05	0.07	1.81	0.06
P × Sub. within-group error	29	(8.44)		(6.07)		(18.00)	

Note. All reported statistics are within subjects. Values enclosed in parentheses represent mean square errors. *f* = Cohen's *f*; Sub. = subjects.
* $p < .05$. ** $p < .01$.

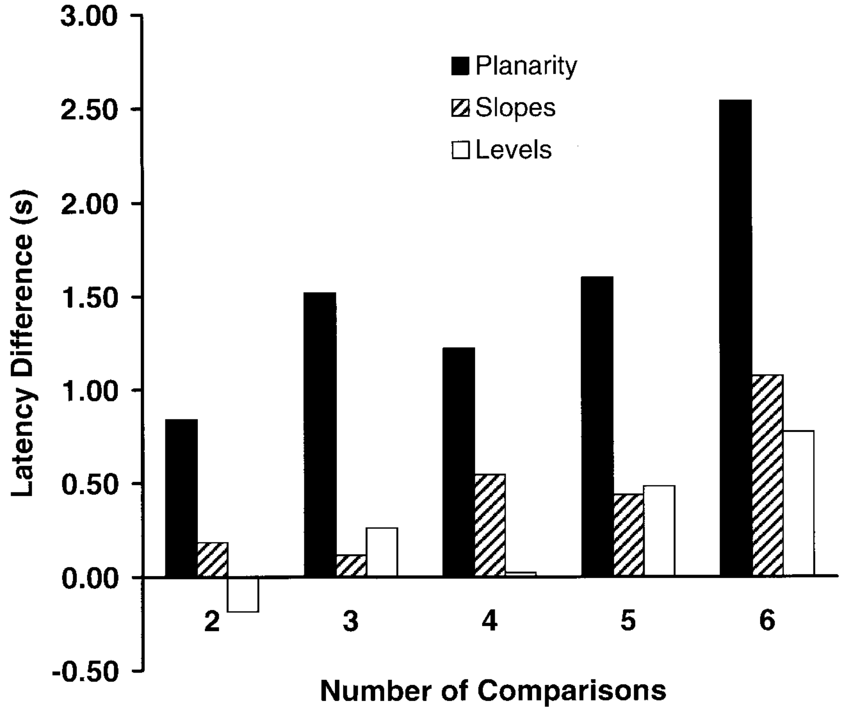

Figure 8. Experiment 2: Latency differences between attributes of visual properties and number of comparisons.

the relevant element *g.* The area surrounding a line crossing does not tell the reader's eyes which way to go.

To test if it is the general disarrangement in crossed drawings, or the crossing of lines present for specific questions with elements whose connecting lines involved crossings, we tested yes questions whose elements did not involve crossed lines, either in noncrossed graphs or (by definition) in crossed graphs. Questions 9, 13, 17, and 25 (see Table 3) allowed for such a test. They involved elements *a, b, c, g,* and *i,* whose interconnecting lines did not cross in any graph. The mean median latency of 9.10 s ($SD = 2.13$ s) for noncrossed graphs was considerably smaller compared with 10.47 s ($SD = 2.57$ s) for crossed graphs, $F(1, 29) = 34.41$, $MSE = 0.82$, $f = 1.19$, $p < .01$. This indicated that it is the general disarrangement present in crossed drawings that causes the slower comprehension speed.

Table 7
Experiment 2: Analysis of Variance for Visual Planarity and Slopes and Number of Comparisons (High vs. Low)

Source	*df*	*F*	*f*
Planarity (P)	1	93.52**	3.22
Comparisons (C)	1	531.47**	18.23
P × C	1	15.46**	0.53
P × Sub. within-group error	29	(0.94)	
Slopes (S)	1	6.93*	0.24
Comparisons (C)	1	488.00**	16.86
S × C	1	9.00**	0.31
S × Sub. within-group error	29	(1.87)	

Note. All reported statistics are within subjects. Values enclosed in parentheses represent mean square errors. *f* = Cohen's *f;* Sub. = subjects.
* $p < .05$. ** $p < .01$.

In Experiment 2, we systematically manipulated question demands by varying the number of comparisons required by a question and by considering yes and no questions. The number of necessary comparisons among elements of an ordered set also has a high impact on speed of comprehension. As expected, speed of comprehension systematically decreases with increasing number of comparisons necessary for answering questions. As expected, this effect is less pronounced for no questions. Whereas participants need to compare each element involved in yes questions, they can answer a no question as soon as they find an element that is not in the ordering relation. In that sense, no questions are less demanding than yes questions, even though they involve the same number of elements. Our data suggest that readers can use this characteristic of no questions to deny those questions more rapidly, at least for questions involving many comparisons (see Figure 7).

The joint analysis of properties of the drawings and properties of the questions confirmed all the previous conclusions. When yes questions were considered, only the effects of planarity and slopes increased with the number of comparisons. For no questions, only the influence of planarity was present and increased with number of comparisons. The effect of slopes was not strong enough to emerge for no questions.

Researchers have often observed that latency differences increase or decrease for one variable depending on another variable (e.g., Teichner & Krebs, 1974), as was the case with planarity and slopes depending on the number of comparisons. The joint data analysis for properties of drawings and yes questions reveals such

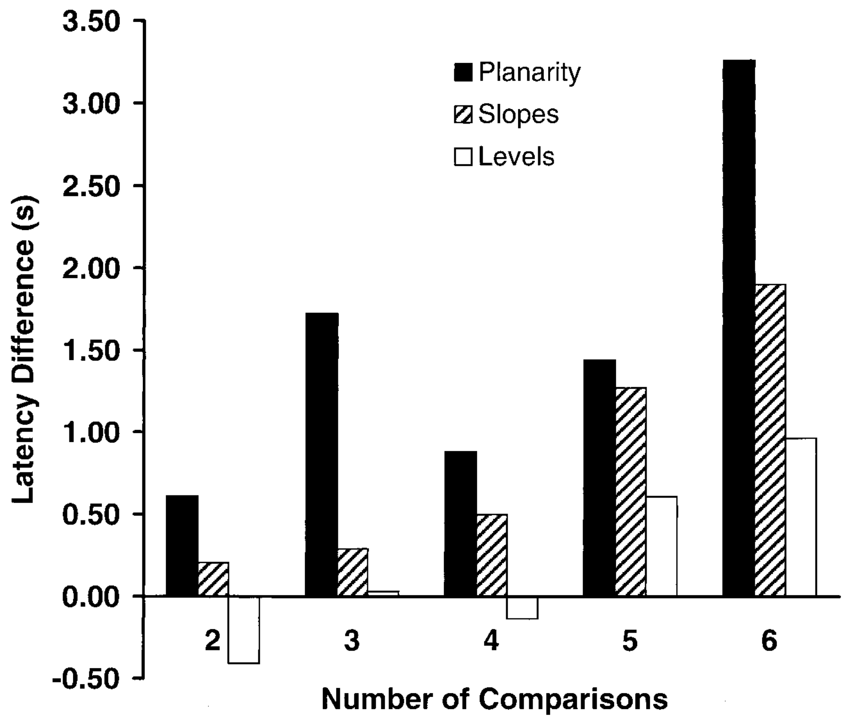

Figure 9. Experiment 2: Latency differences between attributes of visual properties and number of comparisons (yes questions only).

a pattern of results for Experiment 2 (see Figure 9). By and large, the latency differences for visual properties increase quite systematically as a function of the number of comparisons varying from two to six comparisons. This is a consequence of increasing absolute latencies. For example, with two comparisons, the latency (averaged over visual properties) is 7.65 s compared with 16.63 s for six comparisons.

This sort of interaction can be interpreted as follows: The advantage for speed of comprehension already present in simple questions increases step-by-step, the more demanding a question is. In other words, the more demanding the information to be obtained from the drawing is for the graph reader, the more it pays to have the desirable attributes realized in the drawing. Consequently, the strongest effects were obtained for yes questions involving a large number of comparisons.

Visual properties are, in principle, not independent of each other. Reconsider, for example, the simple ordered set and its visualizations in Figure 2. Line crossings, as in the left drawing, were avoided by introducing more slopes in the middle drawing and by drawing a nonhorizontal instead of a horizontal drawing. A desirable attribute was realized at the cost of two other desirable attributes. Interestingly, in our experiments we found no stable interactions among visual properties (besides hardly interpretable interactions of planarity and levels in Experiment 1b, as well as of slopes and levels in Experiment 2, both because of no questions). Thus, preliminary design recommendations are straightforward: Visualization of planarity facilitates comprehension more than each of the other properties and should be given precedence in the design of upward drawings. Planarity pays even for simple questions and readers with little knowledge. Also, for the approval of questions, upright drawings are clearly preferable to horizontal drawings, which seem to have no influence at all.

Our results can be interpreted within the framework provided by Kosslyn (1989), who specified acceptability principles for graphs at the syntactic, semantic, and pragmatic levels of analysis. They are based on general psychological findings on, for example, visual processing, the Gestalt laws, and comprehension research. We focus on the analysis at the syntactic and semantic levels. The syntactic level of analysis deals with basic graphic constituents and their primary influence on early stages of visual information processing.

Crossed drawings may involve several superimposed, irregularly shaped polygons resulting in a major disarrangement, which may have impaired visual segregation and discrimination of interconnecting lines, leading to deteriorated identification. Thus, crossed drawings violated the principle of perceptual apprehension. Line crossings themselves may affect early stages of visual information processing. In their theory of preattentive vision, Julesz and Bergen (1983) proposed the existence of feature detectors, one of which should be sensitive to crossings. There may even be neurons in the human visual system that are specialized in the recognition of crossed lines, making crossings a salient property of a drawing. Such salient properties are processed in precedence, and draw attention and distract the visual system from the message of the drawing. Therefore, crossed upward drawings violated Kosslyn's (1989) principle of processing priorities, which states that only important parts of the display should be chosen to be noticed with priority.

Similar arguments apply to visual slopes. Leeuwenberg (1971, p. 331) stated that "every length or angle that differs from another in a shape corresponds to an information unit," thus increasing the complexity of slanted drawings measured in terms of structural information theory (e.g., Leeuwenberg, 1969).

The visual system is sensitive to orientation (Kolb & Whishaw, 1980). Neurons at various levels of the visual system respond to lines or shapes at particular orientations. It is desirable to draw lines with distinct slopes in order to facilitate their discrimination (principle of perceptual apprehension). It is easier to accomplish this if the drawing includes only a small number of slopes, as is the case in upright drawings. Moreover, a slanted drawing may cover a larger drawing area, as is the case for some of the drawings in our experiments (see Figure 3). As a consequence, graph readers may need more time (and fixations) to search such a graph.

Most of the ordering structure of the visualized information is conveyed in the (upward) directedness. An upright drawing might best reflect the directional nature of its ordered information at an early stage of visual information processing. This supports later stages of information processing and follows Kosslyn's (1989) principle of compatibility, which states that the visual pattern itself should reflect the properties symbolized in a graph.

In horizontal upward drawings, grouping effects may occur for dots drawn on the same horizontal. Grouping or configuration of objects or parts of objects are vital processes in early stages of information processing (principles of perceptual organization and apprehension). By the Gestalt principle of good continuation, a series of horizontally adjusted dots creates the impression of a line, and thus emphasizes the relatedness of the respective elements.

The missing effect of visual levels may be explained by an analysis on the semantic level, which concentrates on the meaning of the symbols of a graph and what they represent. For example, the visual pattern of horizontally adjusted dots in horizontal drawings reflects their common property of being a neighbor of the same element in the ordered set. A horizontal drawing of an ordered set should be easy to interpret because the neighboring relation among the elements (which constitutes the order relation) is provided in a consistent way (principle of compatibility).

From the syntactic analysis we concluded that dots drawn at the same height are likely to be grouped together. Horizontally aligned dots that do not represent neighboring elements of the same upper or lower element can also be present in a horizontal drawing. They may also be grouped together. Additional processing in later stages might be necessary to determine whether these dots are related by the neighboring property. Grouping may only accelerate comprehension if all the grouped dots actually represent neighboring elements. If they do not, a horizontal drawing might slow down comprehension.

There are two possible explanations for the missing effect of visual levels in our experiments. First, in all horizontal upward drawings there were horizontally adjusted dots that did not represent neighboring elements of the same element. For example, elements *b, c,* and *d* (neighbors of element *a*) were aligned with element *e,* which is not a neighbor of *a* (see Figure 3). This design may not be a consistent way of presenting neighboring information and might violate the compatibility principle. Second, a levels effect may be more likely to occur when specific questions that ask for neighboring elements are posed rather than the more general questions used here.

In summary, our results and analysis suggest that the visual properties of planarity and slopes affect visual information processing, beginning at the very early stages of detection and discrimination relevant on the syntactic level. Well-known findings and principles, such as evidence from visual neuroscience and the Gestalt laws (e.g., good continuation) might play a central role in the course of visual information processing of upward drawings. Acceptability principles (e.g., perceptual apprehension, processing priorities, compatibility) are violated by crossed upward drawings, in particular. Whereas visual slopes and levels may also generally affect speed of comprehension, these effects may be reduced by factors such as the discriminability of many steeply drawn lines and grouping of horizontally aligned dots that do not represent neighboring elements.

In order to gain more detailed insight into comprehension of upward drawings, more specific models are necessary. For a better understanding of comprehension of visualized ordered sets, specific assumptions regarding the underlying cognitive mechanisms must be tested; specifically, to establish which processing stages are affected by visual properties. Our results provide a starting point for such research on the psychology of visualized nonnumerical information.

References

Barwise, J., & Etchemendy, J. (1991). Visual information and valid reasoning. In W. Zimmermann & S. Cunningham (Eds.), *Visualization in teaching and learning mathematics* (pp. 9–24). Washington, DC: Mathematical Association of America.

Butler, D. L. (1993). Graphics in psychology: Pictures, data, and especially concepts. *Behavior Research Methods, Instruments and Computers, 25,* 81–92.

Cleveland, W. (1993). *Visualizing data.* Summit, NJ: Hobart Press.

Cleveland, W. (1994). *The elements of graphing data.* Summit, NJ: Hobart Press.

Czyzowicz, J., Pelc, A., & Rival, I. (1990). Drawing orders with few slopes. *Discrete Mathematics, 82,* 233–250.

Davey, B. A., & Priestley, H. A. (1990). *Introduction to lattices and order.* Cambridge, England: Cambridge University Press.

Goldin, G. A. (1985). Thinking scientifically and thinking mathematically: A discussion of the paper by Heller and Hungate. In E. A. Silver (Ed.), *Teaching and learning mathematical problem solving: Multiple research perspectives* (pp. 113–122). Hillsdale, NJ: Erlbaum.

Guri-Rozenblit, S. (1988). The interrelations between diagrammatic representations and verbal explanations in learning from social science texts. *Instructional Science, 17,* 219–234.

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of Memory and Language, 32,* 717–742.

Hollands, J., & Spence, I. (1998). Judging proportion with graphs: The summation model. *Applied Cognitive Psychology, 12,* 173–190.

Julesz, B., & Bergen, J. (1983). Textons, the fundamental elements in preattentive vision and perception of textures. *The Bell System Technical Journal, 62,* 1619–1645.

Kisielewicz, A., & Rival, I. (1993). Every triangle-free planar graph has a planar upward drawing. *Order, 9,* 1–16.

Kolb, B., & Whishaw, I. (1980). *Human neuropsychology.* New York: Freeman.

Kosslyn, S. (1989). Understanding charts and graphs. *Applied Cognitive Psychology, 3,* 185–226.

Kosslyn, S. M. (1994). *Elements of graph design.* New York: Freeman.

Leeuwenberg, E. L. J. (1969). Quantitative specification of information in sequential patterns. *Psychological Review, 76,* 216–220.

Leeuwenberg, E. L. J. (1971). A perceptual coding language for visual and auditory patterns. *American Journal of Psychology, 84,* 307–349.

Lewandowsky, S., & Spence, I. (1989). The perception of statistical graphs. *Sociological Methods and Research, 18,* 200–242.
Lewis, J. R. (1989). Training students to represent arithmetic word problems. *Journal of Educational Psychology, 81,* 521–531.
Maichle, U. (1994). Cognitive processes in understanding line graphs. In W. Schnotz & R. W. Kulhavy (Eds.), *Comprehension of graphics* (pp. 207–226). Amsterdam: Elsevier.
Mayer, R. E., & Gallini, J. K. (1990). When is an illustration worth ten thousand words? *Journal of Educational Psychology, 82,* 715–726.
Novick, L. R., & Hmelo, C. E. (1994). Transferring symbolic representations across non-isomorphic problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20,* 1296–1321.
Novick, L. R., Hurley, S. M., & Francis, M. (1999). Evidence for abstract, schematic knowledge of three spatial diagram representations. *Memory and Cognition, 27,* 288–308.
Pelc, A., & Rival, I. (1991). Orders with level diagrams. *European Journal of Combinatorics, 12,* 61–68.
Pomerantz, J. L., & Kubovy, M. (1986). Theoretical approaches to perceptual organization: Simplicity and likelihood principles. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance, Vol. 2. Cognitive processes and performance* (pp. 1–46). New York: Wiley.
Rinck, M., & Glowalla, U. (1994). Wissensstrukturierung durch statistische Graphen: Weitere Auswirkungen auf das Verstehen [Structuring knowledge using statistical graphs: Further effects on comprehension]. *Zeitschrift für Experimentelle und Angewandte Psychologie, 41,* 132–153.
Rival, I. (1993). Reading, drawing, and order. In I. G. Rosenberg & G. Sabidussi (Eds.), *Algebras and orders* (pp. 359–404). Norwell, MA: Kluwer Academic.
Roberts, F. S. (1979). *Measurement theory with applications to decision making, utility, and the social sciences.* Reading, MA: Addison-Wesley.
Shah, P., & Carpenter, P. A. (1995). Conceptual limits in comprehending line graphs. *Journal of Experimental Psychology: General, 124,* 43–61.
Spence, I. (1990). Visual psychophysics of simple graphical elements. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 683–692.
Sweller, J., Chandler, P., Tierney, P., & Cooper, M. (1990). Cognitive load as a factor in the structuring of technical material. *Journal of Experimental Psychology: General, 119,* 176–192.
Teichner, W. H., & Krebs, M. J. (1974). Laws of visual choice reaction time. *Psychological Review, 81,* 75–98.
Tukey, J. (1977). *Exploratory data analysis.* Reading, MA: Addison-Wesley.

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