Automatic and directed search processes in solving simple semantic-memory problems

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The cognitive processes involved in simple semantic-memory problems were investigated in four experiments. On each trial of Experiments 1 and 2, two stimulus words were presented, with the instructions to find a third word (i.e., the solution) that, when coupled with each of the stimuli, would yield two word pairs used in everyday language (e.g., *surprise* and *birthday*, for which the solution is *party*). The results of the two experiments indicated that informing the subject whether the solution constituted the first or the second element in the word pairs facilitated both likelihood and speed of solution attainment. In addition, solution attainment was relatively high for items based on frequently used word pairs (Experiment 1) and for items in which the stimuli appear, in everyday language, in a small number of word pairs (Experiment 2). In Experiment 3, the subjects were required to produce word pairs containing one of the two stimulus words from the items used in Experiment 2. Solution production was facilitated by rehearsing the second stimulus word of the specific item. The conclusion, supported by a post hoc analysis of the results of Experiments 2 and 3 (Experiment 4), was that indirect priming from one stimulus word may facilitate solution production from a searched word. These results are interpreted in terms of automatic and controlled processes, and their relevance to two different models for retrieval from semantic memory is discussed.

In several theories of human information processing, a distinction between automatic and controlled/attentional processes has been made (e.g., Hasher & Zacks, 1979; Klatzky, 1984; Posner & Snyder, 1975; Schneider & Shiffrin, 1977). In general, an automatic process is assumed to occur without attention, intention, awareness, or interference with another concurrent mental activity, and it is a process that cannot be easily stopped or changed. In contrast, a controlled process is claimed to be dependent on the limited capacity of attention and to be affected by intentions and expectations. Some research (e.g., Neely, 1977; Posner & Snyder, 1975; Stanovich & West, 1981) suggests that an automatic process is faster than an attention-demanding process, but Shiffrin, Dumais, and Schneider (1981) conclude that it is not easy to differentiate between the two types of processes, which are presumably involved in all tasks. Similarly, it recently has been proposed that automaticity should be applied to components of behavior rather than to behavior as a whole (Jonides, Naveh-Benjamin, & Palmer, 1985).

The present work was intended to investigate automatic as well as controlled processes in retrieval from semantic

memory (Tulving, 1972), utilizing a task based on the Remote Associates Test (RAT), originally devised by Mednick (1962) as a measure of creativity. The subject is presented with two-element problems, each requiring a search for one word (i.e., the solution) that, when coupled with each of the two stimulus words (i.e., problem elements), results in two word pairs that are used in everyday language (i.e., solution requirements). For example, the subject may be presented with the words *surprise* and *birthday*, for which the solution is *party*, on the basis of the existing word pairs *surprise party* and *birthday party*.

It is assumed that following the assimilation of task requirements and the encoding of problem elements into their representations in semantic memory, solution attainment is preceded by the following operations: (1) choosing or focusing on one problem element, (2) producing candidates for solution from this element, and (3) evaluating each candidate for its compatibility as a solution to the problem, according to criteria based on solution requirements. Each of these operations may involve both automatic and controlled processes, although the extent of involvement of each type of process to each operation may differ.

We shall assume here that semantic memory is composed of nodes representing words, or concepts, with several types of links between these nodes (see Collins & Quillian, 1969, 1972). Thus, each word pair is represented by two nodes, or two elements, with a specific type of link between these elements. Upon stimuli presentation, an automatic search process is assumed to be initiated. This type of process can be expressed, for example, in an automatic spread of activation in the memory

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system, the magnitude of which has been claimed to be directly related to the strength of links between nodes and to be inversely related to their number (Collins & Loftus, 1975). It is further maintained that an automatic search is dependent on link characteristics, and therefore Operation 2 will be mostly affected by it, candidates for solution produced, for example, according to the strength of links between them and problem elements in semantic memory.

The controlled processes involved in solution attainment, termed here *directed search* processes, are presumed to require attention and therefore can be applied to only one problem element at a time. Operations 1 and 3 apparently involve directed, attentional, serial search to a great extent. Therefore, these operations can be affected by expectations based on any additional information given to or inferred by the problem solver. For example, the problem solver may possess information that will eliminate certain search directions. Accordingly, the initial choice of stimuli for further processing, as well as the decisions that follow evaluation checks, will be determined.

The aim of the first two experiments was to investigate automatic and controlled processes in finding words that constitute the solutions to simple semantic-memory problems. To investigate the two types of processes, two classes of variables were manipulated. Automatic processes are assumed to depend on the strength and number of links between concepts in the memory network. Therefore, the strength and uniqueness of the stimulus-solution connections were investigated, with the expectation that strong or unique connections will lead to easy solution attainment. Furthermore, if controlled search plays a significant role in solution attainment, prior information on solution direction should facilitate solution attainment. Thus, giving the subject certain information on the direction of the solution (i.e., whether it constitutes the first or the second word in the word pairs on which the item was based) should lead to easy solution attainment.

EXPERIMENT 1

The notion that frequency determines strength of associations has been presented by philosophers (see Bor-ing, 1957), learning theorists (see Deese & Hulse, 1967), and memory investigators (e.g., Anderson, 1983), but the frequency of joint occurrence of words in the everyday use of the language has not been investigated in semantic-memory studies. It is assumed here that when the subject is presented with the problem elements (e.g., *birthday* and *surprise*), arriving at the solution (i.e., *party*) is partly determined by the frequency of everyday usage of the word pairs *birthday party* and *surprise party*. Hence, the first hypothesis is that solution attainment will be more facilitated as the word pairs on which the problems are based are more frequent.

Direction of association also has been assumed to affect speed of learning (see Deese & Hulse, 1967; Paivio, 1971) and performance in semantic-memory research (Collins & Loftus, 1975; Warren, 1974). Word pairs in everyday language are sequentially ordered; therefore, the problems used in Experiment 1 were constructed so that, for each stimulus word, the solution could be either a forward or a backward solution (i.e., the second or the first word in each word pair). The second hypothesis is that the direction of the solution will affect solution attainment, which will be more facilitated in forward-solution problems than in backward-solution problems.

Strength of association between the two words in each word pair, as measured by frequency and direction of the association, is assumed to affect solution retrieval through automatic search processes. In addition, retrieval of the solution is also assumed to depend on directed search processes that are under the subject's control. It is proposed that subjects can selectively search for the solution in either the forward or the backward direction and that search in one direction precludes search in the opposite direction. Thus, providing subjects with information on solution direction is assumed to draw attention primarily to solution candidates in the correct direction, resulting in improved performance.

Finally, it could be surmised that, when the stimulus-solution links are strong, the benefit from information on solution direction will be small, because the solution will be automatically retrieved, in contrast to weak stimulus-solution links. Thus, the effect of information is expected to be stronger for problems based on low-frequency word pairs or backward solutions. Another measure of strength of links, based on the frequency of solution production from each stimulus word, was also used to test this interaction.

Method

Subjects. Thirty-two first-year psychology students—7 males and 25 females, aged 18–47 years—participated in the main experiment for course credit. All had normal or corrected vision, and, for all, the mother tongue was Hebrew.

Sixty-one additional subjects, similar to the above-described sample, served in pretest and posttest studies, which will be described below.

Stimulus materials. In a pretest study, 30 students rated the frequency of usage of 620 word pairs, selected from the Eben-Shushan Hebrew-Hebrew dictionary (1972), on a 7-point scale (where 7 denotes high frequency). Word pairs that were marked by more than 20% of the subjects as unfamiliar were not chosen for the experiment.

For each word pair, average frequency was computed and classified according to three frequency levels: high (average frequency of 4.95 or higher), medium (between 3.85 and 4.95), and low (3.85 or lower). Items then were chosen according to four combinations of frequency of the two word pairs on which each item was based, 12 items in each combination: high-high, medium-medium, low-low, and high-low frequency levels. The average frequency levels of the four combinations were 5.62, 4.35, 2.93, and 4.26, respectively. Thus, medium-medium and high-low frequency items were similar on average frequency but differed on the levels of the individual word pairs comprising them.

In each of the four frequency levels, the items were distributed equally in regard to solution direction (four items in each direction level): a forward-forward solution (i.e., the second word in each word pair), a backward-backward solution (i.e., the first word in each pair), and a forward-backward or a backward-forward solution (i.e., the first word in one pair and the second word in the other pair). For example, if an item was based on the word pairs *country house* and *house maid*, the stimuli were *country* and *maid* and the solution was a forward solution for the first stimulus and a backward solution for the second.

When selecting items, repetitions of stimuli or solutions were avoided. In everyday language, the stimuli appear in a relatively small number of other word pairs (0-6 in each direction, according to the Eben-Shushan Hebrew-Hebrew dictionary, 1972).

The two stimulus words of each item were typed one above the other. Four sets of 48 slides were prepared, and, in two sets, an X mark preceded or succeeded the words on the slides, depending on the solution direction. The order (top or bottom) of the two stimuli of each item was counterbalanced over the two sets. For the forward-backward items, for half of the items in each frequency level, the backward pair was typed at the top of the slide and, for the other half, it was typed at the bottom; the same was true for the high-low frequency items in each direction level.

Design. Experiment 1 used a $2 \times 4 \times 3$ factorial design, information $\times$ frequency $\times$ direction, with information a between-subjects factor and with frequency and direction within-subjects factors.

Procedure. Sixteen subjects were assigned to each information condition. In the complete-information condition, the subjects were presented with the 48 slides in which solution direction was marked for each stimulus. In the no-information condition, the subjects were presented with the 48 slides in which solution direction was not marked. Each set of 48 slides was presented to 8 subjects; each subject was presented with a different sequence of items, counterbalancing for the order of items from each frequency $\times$ direction cell.

The subjects were tested individually in a laboratory room, seated 1.5 m from a screen. They were instructed that, upon presentation of each slide (which was preceded by a "ready" signal), they should start searching for the solution (i.e., a third word that could be coupled with each of the stimuli to create two separate word pairs commonly used in the language). The subjects were given several examples and were told of the three levels of solution direction. Time allotted for each item was 60 sec.

Items were presented by means of a slide projector. When the correct solution was reached, the subjects were given positive feedback and the next slide was presented. If they responded with an incorrect word, they were told to continue searching. If the solution was not reached within 60 sec, the subject was told the correct solution before being asked to proceed to the next item. This was done to equate knowledge of solutions for all subjects and to prevent the subjects from continuing the search in unsolved items. The subjects also were given six examples before being presented with the 48 items; all subjects correctly solved at least three examples. The whole procedure was tape-recorded.

Results and Discussion

Information on solution direction was manipulated between subjects. Therefore, the two experimental groups were compared on verbal ability measured by a word vocabulary test, which is part of the entrance examinations at the university. The two groups did not differ on this measure [$t(30) < 1$].

Two measures were derived for each item from the tape-recorded data: (1) whether or not the subject arrived at the correct solution during 60 sec and (2) the time it took

the subject to reach the correct solution. Time to correct solution was measured twice, using a stopwatch, to a precision of 0.1 sec, and the average of the two measurements was analyzed.

The first dependent variable to be analyzed was the proportion of correct solutions (PC), calculated for each subject in each frequency $\times$ direction cell. Table 1 presents the PC means for the information $\times$ frequency $\times$ direction combinations. A three-way analysis of variance (ANOVA) showed a significant effect of information [$F(1,30) = 12.77$, $MS_e = 0.08$, $p < .001$]. The complete-information condition led to a higher mean of correct solutions than did the no-information condition (.73 and .63, respectively), with no interaction effects between information and frequency ($F < 1$) or information and direction [$F(2,60) = 1.16$]; the triple interaction also was not significant [$F(6,180) = 1.10$].

A significant effect was found for frequency [$F(3,90) = 10.84$, $MS_e = 0.04$, $p < .0001$], with overall PC means of .77, .61, .67, and .68 for high-high, medium-medium, high-low, and low-low frequency levels, respectively. Thus, items based on frequent word pairs led to more solutions than did the other types of items, but the pattern for the medium and low frequency levels is not monotonic. The effect of direction was significant as well [$F(2,60) = 4.70$, $MS_e = 0.04$, $p < .01$], with PC means of .71, .69, and .64 for the forward-forward, forward-backward, and backward-backward levels, respectively. The significant frequency $\times$ direction interaction [$F(6,180) = 25.05$, $MS_e = 0.04$, $p < .0001$] does not show any specific pattern (see Table 1) and probably stems from other item characteristics that lead to great item variance in cells containing a small number of items.

The averages of mean time to correct solution, calculated for each information $\times$ frequency $\times$ direction cell, are presented in Table 2. A three-way ANOVA showed significant effects for information [$F(1,30) = 5.79$, $MS_e = 59.87$, $p < .05$], frequency [$F(3,90) = 6.22$, $MS_e = 50.92$, $p < .001$], and direction [$F(2,60) = 3.42$, $MS_e = 45.93$, $p < .05$]. The overall effect of information was to speed up the attainment of solutions, with means of 6.4 and 8.3 sec for the complete- and no-information conditions, respectively. In the high-high frequency level, so-

Table 1
Means of Proportions of Correct Solutions for the Complete- and No-Information Conditions

Direction	Frequency			
	H-H	M-M	H-L	L-L
Complete Information				
F-F	.75	.84	.80	.70
F-B	.94	.75	.48	.72
B-B	.81	.38	.83	.78
No Information				
F-F	.64	.67	.78	.50
F-B	.86	.69	.47	.64
B-B	.61	.33	.67	.72

Note—H = high, M = medium, L = low, F = forward, and B = backward.

Table 2
Means of Solution Times (in seconds) for Correct Solutions
for the Complete- and No-Information Conditions

Direction	Frequency			
	H-H	M-M	H-L	L-L
Complete Information				
F-F	6.7	6.9	4.7	8.2
F-B	2.3	3.6	10.1	4.8
B-B	4.9	14.9	5.7	5.0
No Information				
F-F	7.2	5.1	8.3	18.3
F-B	3.0	5.5	9.7	9.4
B-B	4.0	15.3	7.1	7.1

Note—H = high, M = medium, L = low, F = forward, and B = backward.

lutions were attained faster than in all other levels of frequency (4.7, 8.5, 7.6, and 8.8 sec for the high-high, medium-medium, high-low, and low-low frequency levels, respectively), but no differentiation was observed among the medium and low levels of frequency. The direction means were 8.2, 5.9, and 8.0 sec for the forward-forward, forward-backward, and backward-backward items, respectively. Thus, the forward-backward items were performed faster than were items in the other levels of direction. In this analysis, the information $\times$ frequency interaction also was significant [$F(3,90) = 3.04$, $MS_e = 50.92$, $p < .05$]. The means for the complete-information condition were 4.6, 8.3, 6.8, and 6.0 sec for the high-high, medium-medium, high-low, and low-low frequency levels, respectively; the respective means for the no-information condition were 4.7, 8.6, 8.4, and 11.6 sec. Thus, the major difference between the two information conditions was with the low-low frequency items, for which the no-information subjects took much more time to reach the solutions than did the complete-information subjects. The information $\times$ direction and the information $\times$ frequency $\times$ direction interactions were not significant [$F < 1$, and $F(6,175) = 1.26$, respectively; df was smaller than expected, i.e., 175 instead of 180, because a few subjects did not attain any solution in certain cells]. A significant frequency $\times$ direction interaction also was found, as in the PC analysis [$F(6,175) = 11.80$, $MS_e = 43.19$, $p < .0001$].

Because the information $\times$ frequency interaction was significant for the solution-time data, and no other interactions with information were obtained, an additional measure of strength of association was obtained. Following Experiment 1, 31 new subjects were presented with the 96 stimulus words used in the experiment, separately printed on several pages, and asked to produce and write down for each word 1–3 word pairs. These data were used to create a measure of solution dominance—the extent to which the solution was produced from the separate stimulus words for each item (without information on solution direction), measured by counting the number of times each stimulus word produced the solution and by averaging over the two words in each item. Items were divided into

three levels of solution dominance: high, medium, and low, with 16 items in each level. The respective averages of the three levels were 19.37, 10.63, and 4.72.

A two-way ANOVA on the PC scores showed no information $\times$ dominance interaction ($F < 1$). However, a two-way ANOVA performed on the solution-time data showed a significant information $\times$ dominance interaction [$F(2,60) = 4.19$, $MS_e = 12.49$, $p < .05$]. The means for the complete-information group were 3.6, 6.9, and 9.6 for the high, medium, and low dominance levels, respectively; the respective means in the no-information group were 5.1, 7.8, and 15.2. Thus, the effect of information was stronger for low-dominance items than for high-dominance items, as was found for the frequency factor.

To sum up, information on solution direction clearly facilitated both the likelihood and the speed of solution attainment. This result suggests that controlled processes play a significant role in the search for a solution. One possibility is that information on solution direction affects the evaluation operations. Wrong candidates may be rejected faster because they do not match either the known direction in the word from which they were produced or the known direction in the second stimulus word. However, information sped up performance when problems were of low-frequency word pairs or of low-solution dominance, suggesting that information may also affect search operations apparently by allowing attentional resources to be allocated towards specific types of connections. Thus, information may be effective at earlier stages, when the operation of production takes place.

When the problem was based on frequent word pairs, performance was facilitated. In contrast, performance was not affected consistently by the direction of solution. If we assume the words constituting word pairs to be represented as linked nodes in semantic memory, the accessibility of a link probably is determined by the number of times it was encountered in the past and not by the direction in which it was used. Another problem characteristic that may affect solution attainment is the number of candidates for solution, which was tested in Experiment 2.

EXPERIMENT 2

The aims of Experiment 2 were twofold. First, it was intended to investigate the effects of another problem characteristic on solution retrieval. Second, it aimed at replicating the effects of information manipulated in Experiment 1, but under less extreme conditions.

Solution attainment may depend not only on strength but also on the number of links relating nodes in the semantic net. The number of associations (or *fan*; see Anderson, 1983) has, in the past, been found to affect retrieval speed (e.g., Anderson, 1976, 1983; Collins & Loftus, 1975). For the problems used in the present research, each of the two stimuli appeared, in everyday language, in many or just a few word pairs. Hence, it

is hypothesized that solution attainment will be more facilitated as the number of word pairs in which the stimulus words appear is smaller.

In Experiment 2, the effect of information on solution direction was tested by comparing complete information with partial information provided for one of the stimuli. If the directed search is also limited in regard to each stimulus word, such a comparison should still show an advantage for complete information.

Method

Subjects. Forty-eight paid students—16 males and 32 females, aged 18–34 years—participated in Experiment 2. All had normal or corrected vision, and, for all, the mother tongue was Hebrew.

Stimulus materials. Items were chosen according to the number of words that could be coupled with the stimulus word, in the respective solution direction, to create commonly used word pairs (according to the Eben-Shushan dictionary, 1972). A small number of words in solution direction was arbitrarily defined as being in the range of 0–5, and a large number was defined as 6 or more. Items also were selected according to solution direction (i.e., forward or backward solutions), as in Experiment 1. The 40 items finally chosen were distributed according to three levels of the number of words in solution direction that created word pairs with the stimulus word: 8 small-small, 18 small-large, and 14 large-large items. The averages for the three number levels were 2.25, 6.59, and 18.75, respectively. Of the 8 items in the small-small number level, there were 2, 2, and 4 items in the forward-forward, backward-backward, and forward-backward direction levels, respectively. Of the 18 items in the small-large level, there were 4, 4, and 10 in the respective direction levels. Of the 14 large-large items, there were 4, 4, and 6 items in the respective direction levels. Overall, there were 10 forward-forward, 10 backward-backward, and 20 forward-backward solutions, so that when the direction of the solution was provided for one word, the probability of a forward solution in the other was .50. All items were based on word pairs with high or medium average frequency ratings, on the basis of the pretest results described in Experiment 1.

The 40 items were presented on slides, the two stimuli printed one above the other as in Experiment 1. Four sets of 40 slides were prepared. In two sets, the solution direction was marked by an X for one stimulus word only. In one set, the stimulus word appearing at the top of the slide was marked with an X in solution direction, whereas the second word below it was not marked. In the second set, presentation was the same, but order (top or bottom) of the two stimuli on the slide was reversed. In each set, half of the forward-backward items in each number level appeared with the forward-solution stimulus on top; the order of words in the small-large number condition in each direction level was similarly balanced. In the other two sets, arrangement of stimuli was the same, but the X mark preceded or succeeded the two words, according to solution direction, as in Experiment 1.

Design. Experiment 2 used a $2 \times 3 \times 3$ factorial design, information $\times$ number $\times$ direction, with information a between-subjects factor and with number and direction within-subjects factors.

Procedure. Sixteen subjects were assigned to the complete-information condition, 8 subjects presented with one of the 40-item sets in which solution direction was marked for the two stimuli. Thirty-two subjects were assigned to the partial-information condition, 16 subjects presented with one of the sets in which solution direction was marked for one stimulus only. Each of the 4 subjects assigned to each set was presented with a different order of items, counterbalancing for the order of items from each number $\times$ direction cell.

Procedure and instructions to the subjects were similar to those in Experiment 1, but slide changing was monitored by a time counter

and a warning signal was given before the presentation of each slide. Following Experiment 2, each subject was given a word vocabulary test. As in Experiment 1, the entire procedure was tape-recorded and the same measurements were obtained for each item.

Results and Discussion

Information was manipulated between subjects, so the complete-information group and the two partial-information groups were compared on word vocabulary level. No significant differences were obtained [$F(2,45) < 1$].

For each subject, PC and solution time scores were computed for each number $\times$ direction cell. Three-way ANOVAs applied to the data of the two partial-information subgroups showed no differences between the two subgroups and no interactions with the number or direction factors. Thus, the data were collapsed across the two subgroups. Table 3 presents the PC means as a function of information $\times$ number $\times$ direction. A three-way ANOVA showed a highly significant effect of number [$F(2,92) = 162.38$, $MS_e = 0.03$, $p < .0001$], the data suggesting a linear relationship between the number levels and the PC means (.84, .65, and .46 for the small-small, small-large, and large-large levels, respectively). The effect of direction also was significant [$F(2,92) = 7.54$, $MS_e = 0.04$, $p < .001$], as was the number $\times$ direction interaction [$F(4,184) = 6.25$, $MS_e = 0.05$, $p < .0001$]. The effect of direction was as in Experiment 1 (.68, .68, and .61 for the forward-forward, forward-backward, and backward-backward levels, respectively), and the interaction did not show any specific pattern. The effect of complete information versus partial information was marginally significant in the PC analysis [$F(1,46) = 2.92$, $MS_e = 0.05$, $p < .10$]. Complete information led to more solutions than did partial information (.68 and .63, respectively), but the effect was smaller than in Experiment 1. No interactions were found between information and the other two factors.

The means of the solution-time data are presented in Table 4. The effects of information and number were significant [$F(1,46) = 3.93$, $MS_e = 53.43$, $p < .05$, and $F(2,92) = 14.54$, $MS_e = 40.33$, $p < .0001$, respectively], but not the effect of direction [$F(2,92) = 1.43$]. Thus, information was effective in speeding up solution

Table 3
Means of Proportions of Correct Solutions for the
Complete- and Partial-Information Conditions

Direction	Number		
	S-S	S-L	L-L
Complete Information			
F-F	.97	.58	.52
F-B	.88	.72	.47
B-B	.75	.81	.39
Partial Information			
F-F	.91	.57	.52
F-B	.86	.70	.46
B-B	.72	.59	.39

Note—S = small, L = large, F = forward, and B = backward.

Table 4
Means of Solution Times (in seconds) for Correct Solutions for the Complete- and Partial-Information Conditions

Direction	Number		
	S-S	S-L	L-L
Complete Information			
F-F	4.1	7.8	9.8
F-B	4.9	7.0	9.6
B-B	5.4	10.0	5.4
Partial Information			
F-F	4.1	8.2	11.4
F-B	7.2	8.5	13.5
B-B	8.0	10.1	6.7

Note—S = small, L = large, F = forward, and B = backward.

attainment, as in Experiment 1, with means of 7.1 and 8.6 sec for the complete- and partial-information groups, respectively. The overall means of the number factor were 5.6, 8.6, and 9.4 for the small-small, small-large, and large-large levels, respectively. Thus, as the number of word pairs became larger, solution speed was retarded. No other effects were significant, except for the number $\times$ direction interaction [$F(4,176) = 7.30$, $MS_e = 38.50$, $p < .0001$].

To sum up, the results of Experiment 2 replicate those of Experiment 1 in showing that the amount of information given on solution direction affects performance. Even when information is provided for one stimulus word, performance is lower than that observed in a condition in which information is provided for the two stimulus words. In addition, the number of word pairs in which the stimuli appeared highly affected solution attainment in the predicted trend, whereas the effect of direction was weaker, as it was in Experiment 1.

EXPERIMENT 3

The results of Experiments 1 and 2 indicate that information on solution direction is effective in facilitating solution attainment. This can be taken as evidence for a controlled, directed search process that is serially conducted. Strength and uniqueness of links in the semantic network also led to facilitation in solution attainment, and these effects were seen as evidence for the automatic components in the search process.

Experiment 3 was intended to investigate the indirect effects of automatic processes on solution attainment. We suggest that when one problem element is searched, indirect automatic priming from the other element facilitates solution production from the searched element. The task used in Experiments 1 and 2, however, could not be utilized, because the explicit requirement to search for a common solution presumably leads to alternating directed search from each of the stimulus words. Hence, in Experiment 3, production of the solution, without specifically searching for it, was measured in a priming task based on the original search task.

The effects of primes have been investigated in relation to activation and attentional processes in semantic memory (e.g., Neely, 1977; Stanovich & West, 1981; Tweedy, Lapinski, & Schvaneveldt, 1977; Warren, 1977). The main findings suggest that, when automatic processes are involved, relevant primes speed up the production of the required responses, whereas irrelevant primes do not interfere with performance. Thus, in Experiment 3, the subjects were required to produce word pairs to one stimulus word and, at the same time, to engage in subvocal rehearsal of another word. For some of the items, the rehearsal word was related to the solution (i.e., the second stimulus word of the original problem); for other items, it was not related. This task shared a similar component with the original task used in Experiment 2: the requirement was to search for word pairs. In comparison with priming in a free-association task (Cramer, 1964), the rehearsal requirement of an additional word increases the cognitive load of the task and leads the subject to repeat the priming word while producing word pairs. These aspects of the task made it as similar as possible to the original search task. Finally, using unrelated primes or, in some of the items, not using any primes, lowered the chances that the subject would intentionally search for a solution although he/she was not required to do so.

Method

Subjects. Forty-eight psychology students—16 males and 32 females with an age range of 19–42 years—participated for course credit. All had normal or corrected vision, and, for all, the mother tongue was Hebrew.

Stimulus materials. The 40 items presented in Experiment 2 in one of the partial-information conditions were used to construct the items of Experiment 3. The stimuli presented in Experiment 2 with solution direction (i.e., marked by an X) were chosen to be the production words; the stimuli presented without an X were chosen to be the rehearsal words (i.e., the primes).

Separate slides were prepared for production and rehearsal words. The production word was typed in the center of the slide, with an X typed according to solution direction. The rehearsal word appeared without an X.

The 40 items were randomly divided into three sets, with either 13 or 14 items in each set, with the following restrictions: (1) Easy and difficult items, according to performance in Experiment 2, were divided equally between the three sets and (2) each set included a similar number of items from each direction $\times$ number combination.

Design. Experiment 3 used a within-subjects design; each subject was tested under three experimental conditions: relevant rehearsal, irrelevant rehearsal, and no rehearsal.

Procedure. When a set of items was presented in the relevant-rehearsal condition, the rehearsal word was the second stimulus word in the original item. When a set was presented in an irrelevant-rehearsal condition, the rehearsal words were chosen from the remaining 26 or 27 stimuli and were paired randomly with them, ensuring that the unrelated word did not lead to the solution of this item and that it did not create a word pair with the production word itself. In the no-rehearsal condition, items were presented without a rehearsal word.

There were three groups of 16 subjects each that differed only in the sets of items, which were assigned to the three conditions. The three sets of items were assigned to the relevant-, irrelevant-,

and no-rehearsal conditions in each group, according to a Latin square design. In each group, each of 4 subjects was presented with a different sequence of items, as in Experiment 2. The 4 subjects also were presented with the same irrelevant rehearsal words, which were re-paired with the production words for another subgroup of 4 subjects.

The subjects were tested individually in a laboratory room. They were instructed that the task was to produce, upon presentation of the production word, as many word pairs as they could remember in the direction marked by the X (e.g., if the X succeeded the word, they were to search for word pairs in which the production word was the first word). They also were told that, in certain items, another word would precede the production word. In those cases, they should rehearse the former word, because their memories for it would be tested when the time allotted for word-pair production was over. Each subject was told that he/she would be stopped after a certain time interval and that then he/she would be asked to immediately recall the rehearsal word. Three examples were given before testing started, two examples were presented with rehearsal words that did not lead to a common solution with the production words, and production was stopped after 15, 30, and 45 sec.

In each trial, a warning signal was sounded, followed by a 4-sec presentation of a slide that contained either a rehearsal word or was empty. This was followed by the presentation of the slide containing the production word for a maximum of 60 sec. If the subject produced the pair that included the solution, he/she was stopped 5–10 sec afterwards and, in the rehearsal conditions, was asked to recall the rehearsal word. The purpose of stopping the subject was to prevent knowledge of the exact time of testing. It was assumed that this procedure would increase the chances of rehearsal while producing word pairs. The whole procedure was tape-recorded, as in Experiments 1 and 2. Following Experiment 3, the subjects were interviewed in order to find out how much they had guessed about the purpose of the experiment. Only 4 subjects suspected a connection between the prime and the production word, and none referred to the possibility that the two words could be related via a common element.

Results and Discussion

PC and solution time scores were computed for each subject in each condition, as in the first two experiments. The scores were computed over the 13 or 14 items in each condition. A one-way ANOVA showed a significant effect for PC [$F(2,94) = 5.73$, $MS_e = 0.02$, $p < .01$], with means of .50, .41, and .42 for the relevant-, irrelevant-, and no-rehearsal conditions, respectively. The same effect was obtained when analyzing the solution-time data [$F(2,94) = 3.72$, $MS_e = 27.09$, $p < .05$], with means of 8.2, 10.1, and 11.0 sec for the relevant-, irrelevant-, and no-rehearsal conditions, respectively (the solution-time data do not include rehearsal-word presentation time). These results indicate that the related prime facilitated both the likelihood and the speed of solution production. The fact that the PC mean in the irrelevant-rehearsal condition was almost identical to the no-rehearsal mean indicates that the unrelated prime did not interfere with the production of the solution. The solution-time data show a small difference between the two conditions because the irrelevant-rehearsal mean was somewhat lower than was the no-rehearsal mean, the opposite of an interference effect. No interference from unrelated primes was observed, so it is unlikely that the subjects deliberately searched for candidates from the prime and evaluated their

possible matches with the production word. Thus, the conclusion is that solution production, which is affected by related primes, is the result of automatic rather than directed search processes.

Performance in the relevant-rehearsal condition in Experiment 3 can be compared with performance in the partial-information condition of Experiment 2, in which the same stimuli were presented. The PCs were .50 for the priming condition and .64 for the explicit-search condition. Thus, when a search for a solution was conducted, performance was better than performance based on priming effects only. This result can be taken as indirect evidence for the involvement of controlled processes when an explicit search for a solution is required.

Finally, for each condition in Experiment 3, PC scores were computed for each item, as well as for the partial-information group of Experiment 2. Pearson correlations were calculated over the 40 items, between the data of the partial-information group and the relevant-, irrelevant-, and no-rehearsal data. The obtained r values were .71, .51, and .53, respectively ($p < .01$). There appears to be a stronger relationship between performance in the explicit-search group and the relevant-rehearsal condition. Hence, there was a greater similarity between the two conditions in which the two stimuli leading to the solution were presented. This result suggests some overlap in the processes underlying the two tasks. It could be concluded that in the problem-solving task itself, when attention is drawn towards one element, indirect automatic priming from the other facilitates solution retrieval from the searched element. To further substantiate this interpretation, additional analyses are presented in the next section.

EXPERIMENT 4

The evidence presented in Experiment 3 for the indirect effects of primes on solution production leads to the conclusion that, in the original search task, the solution may be indirectly primed in semantic memory by a problem element that is not attended to at a certain moment. The purpose of this section is to further test this idea by applying a post hoc analysis to the data of Experiments 2 and 3.

One alternative to the above conclusion, which we intend to reject by the following analysis, is that solution retrieval is based exclusively on directed search processes that are serially conducted. The search is alternating between the two problem elements, and each element is independently searched as if it were the only element in the problem. Following this type of a serial search model, it can be assumed that solution is attained from one problem element with a probability of P_1 , and from the other element with a probability of P_2 . The probability of retrieving the solution independently from the two problem elements, P_{12} , could be calculated according to the following equation:

$$P_{12} = P_1 + (1 - P_1) \cdot P_2. \quad (1)$$

The basic assumption of a serial search model is that the search from two elements is carried out sequentially, so a search in time interval T should be divided between the two elements. If we assume that, on the average, equal search time is allotted to each element, then the prediction equation should be based on the probabilities of solution retrieval from each element in half of the time interval, $T/2$, and therefore

$$P_{12,T} = P_{1,T/2} + (1 - P_{1,T/2}) \cdot P_{2,T/2}, \quad (2)$$

where $P_{12,T}$ is the probability of solution attainment in time interval T , and $P_{1,T/2}$ and $P_{2,T/2}$ are the probabilities of solution production from each element in $T/2$.

The following predictions are made: (1) If performance is based exclusively on serial search, observed performance and performance as predicted from Equation 2 should not differ, and (2) if observed performance is found to be higher than that predicted by Equation 2, it can be suggested that other effects increase solution attainment over and above directed search effects.

Method

The estimates used for the simple probabilities, $P_{1,T/2}$ and $P_{2,T/2}$, were based on the proportions of solutions produced separately to the stimulus words contained in the 40 items of Experiment 2. The proportions for one set of 40 stimulus words (one word from each item) were derived from the results of the no-rehearsal condition in Experiment 3 (i.e., the condition in which the subjects were presented with one word from each item of Experiment 2 and asked to produce word pairs in solution direction without a rehearsal word preceding the production word). The other set of proportions was derived from the results of an additional test. Sixteen new subjects were presented with the second set of 40 stimulus words and asked to produce word pairs in solution direction during 1 min. The observed proportions of solutions attained in a problem-solving task were those collected in Experiment 2 for the complete-information condition (i.e., with the direction of solution provided for both stimuli).

Results and Discussion

The solution frequency distributions along the time axis were positively skewed. According to Equation 2, estimates of $P_{1,T/2}$ and $P_{2,T/2}$ should be based on half of the total time required to arrive at a solution in the two-element problem. Taking into account the shape of the distributions, these estimates were based on proportions calculated for the first half of the time durations tested.

Proportions of observed solutions in the explicit-search task were calculated for the total time of 60 sec. Therefore, estimates of $P_{1,T/2}$ and $P_{2,T/2}$ were based on proportions of solutions produced from each stimulus during the 30 sec following item presentation. The three sets of proportions are given in the Appendix.

Average observed performance during a time duration of 60 sec was .65, significantly higher than the average of .59 predicted from Equation 2 [$t(39) = 2.06$, $p < .05$]. Thus, the effect of searching for a common solution from the two stimulus words is to increase solution production over and above what might be predicted according to a one-process serial search model. We also have calculated the estimates of $P_{1,T/2}$ and $P_{2,T/2}$ during

the first 4 sec following item presentation, when approximately 50% of all solutions were produced. The observed proportion of solutions attained for the two-element problems was thus calculated for the 8-sec duration following problem presentation. These proportions also are presented in the Appendix. The difference between observed and predicted performance in this comparison was indeed larger, with mean proportions of .50 and .37, respectively [$t(39) = 4.35$, $p < .001$]. These results support the conclusion derived on the basis of Experiment 3 data, namely, that indirect priming contributes to solution production in the search task investigated in the present research.

GENERAL DISCUSSION

In the present research, simple problems based on elements from everyday language were used to investigate automatic and controlled processes in retrieval from semantic memory. The results showed solution attainment to be facilitated by certain problem characteristics that are assumed to represent either strength (word-pair frequency; Experiment 1) or uniqueness (number of word pairs; Experiment 2) of links in a semantic-memory network. The results of Experiment 3 indicate that solution production was facilitated by related primes, and the results of Experiment 4 further support the interpretation that indirect priming effects contribute to solution attainment. These data presumably reflect automatic processes in solution retrieval.

Valid information on solution direction, manipulated in Experiments 1 and 2, proved to be beneficial in solution attainment, and specifically so in problems characterized by infrequent word pairs or by low dominance of the solution. The data also show that an explicit search for a solution leads to a better performance than does searching for word pairs under related primes. These results were attributed to directed search processes, which suffer from attentional limitations but are under the subject's control.

While the data summarized above are interpreted as representing the effects of automatic and controlled processes, we should inquire further about the kind of semantic-memory model that can best be applied to these data. Two retrieval models are described below, and the fit of the present results to each model is discussed.

One of the first semantic-memory models was the network model presented by Collins and Quillian (1969, 1972), who saw semantic memory as a net of interrelated nodes, each node representing a different concept. Collins and Loftus (1975) extended this model by adding several assumptions about the activation processes that account for retrieval from the memory network. Thus, when a concept is processed or primed, activation is released from the node representing it and spreads to other, related nodes in a decreasing gradient (Collins & Loftus, 1975). The spreading-activation notion was supported in several experiments (see Collins & Loftus, 1975; Schvaneveldt & Meyer, 1973; Warren, 1977) that showed

facilitation in the production, reading, or lexical judgment of concepts preceded by the presentation of related concepts. Collins and Loftus also suggested that only one concept can be actively processed at a time, but activation released from that concept then independently spreads to and from other concepts. Hence, the implicit assumption is that spread of activation is conducted automatically, whereas controlled processes are used when an evaluation of the activated concepts is required.

More recently, a compound-cue theory was presented by Ratcliff and McKoon (1988), designed specifically to explain the effects of primes on responses to related items. According to the model, prime and target join together to form a compound cue that, in turn, is compared with items in long-term memory (i.e., semantic memory). If prime and target are associated in long-term memory, the match is greater than if they are not associated and the response is facilitated. Ratcliff and McKoon (1988) also compare the spreading-activation and compound-cue theories and describe two experiments that support the latter theory.

In the present investigation, word pairs were used to construct simple problems. Following a *link* model of the type presented by Collins and Loftus (1975), a word pair may be represented in semantic memory as two nodes connected by a specific link that conveys the special meaning of the word pair. When one of the words included in a word pair is processed, activation spreading in all links also will prime the second word in the word pair. On the other hand, following a *compound* model, such as that presented by Ratcliff and McKoon (1988), a word pair should be described as a compound consisting of two elements. When one word is presented, it evokes the whole compound, and thus the other is apprehended. Three main aspects of the present results can be discussed in light of these two different notions: the effects of problem characteristics, indirect priming, and information on solution direction.

The effect of frequency of word pairs on solution attainment can be accommodated quite well by both models. Thus, a frequent pair is either a pair with a highly accessible link between the two words constituting it or a compound that is easily accessible. However, the interpretation of the effect of number of word pairs is more complicated. According to a link model, the number of word pairs can be translated into the number of links related to the nodes representing the stimuli, with less activation in each link as the number gets higher. However, a compound model lacks a structure to relate compounds with common elements. Therefore, each should be retrieved and then examined through the evaluation operation. Thus, the two models differ in the type of operation assumed to underlie the effect. As for the direction of the solution (i.e., forward or backward), the present results do not show any consistent effect for a forward direction, supporting a compound model in which either cue can prime the whole unit (see Ratcliff & McKoon, 1988, for a discussion of this point).

In our opinion, the second type of effect, that of indirect priming, is more supportive of a link model than of a compound model. According to the former, the effect of related primes is through the activation of the specific link that leads to the solution. Thus, the production of the solution from the searched element is facilitated, because the solution is also activated from another source. It is difficult to explain the indirect priming effect by a compound model because, as mentioned above, there is no structure for relating compounds. It could be claimed that the system retrieves the compounds in which the prime appears and then evaluates them for their match with the production word. However, this possibility has already been rejected in Experiment 3 on the basis of no interference effects from unrelated primes.

The third type of effect, namely, the effect of information on solution direction, can be explained by the compound model only by the use of the evaluation operation, and it is difficult to see how such a model may accommodate the interaction between information and frequency. As already discussed in Experiment 1, the link model can allow effects of information during the production operation, as well as during the evaluation phases.

To sum up, it seems that the results of the present investigation do not support either model exclusively. More specifically, the effects of information and indirect priming seem to be more problematic for a compound model, although the underlying processes should be elaborated on even if a link model is adopted.

In our opinion, the activation notion (Collins & Loftus, 1975) can be used to explain the effects of both indirect priming (i.e., automatic processes) and information (i.e., controlled processes). When a node is activated, automatic activation will spread to all links in direct relation to their strength. However, following Koriati (1981) and Martindale (1981), attention directed towards a specific concept can highly activate it, while activation of other related concepts will be inhibited. Thus, certain links can be highly activated at the expense of other links. Such a process will depend on the inferred and given knowledge concerning the task, the nature of the elements that constitute the problem, and the required response. This knowledge directs the search towards certain memory nodes and towards certain groups of links connected to these nodes. Thus, one possibility of explaining the effects of information on solution direction is that such information releases more activation in that direction. When no explicit search for a solution is required, related primes facilitate performance because some activation is always automatically spreading in all links. The effect of priming, however, was found to be weaker than the effect of an explicit search. This result also leads to the conclusion that activation of the solution will depend on the amount of explicit information given on problem requirements.

Another possibility is to keep both compound and link activation notions, but to assume that each node in the memory network represents either simple elements (i.e.,

single words or concepts) or compounds based on several elements. It follows that word pairs will be represented in one node but will be linked to other nodes that represent other word pairs with common elements or single elements, such as the single words that constitute the word pairs. Processing one node will lead to the activation of related nodes, including nodes that represent word pairs. Such a model can accommodate all of the results presented in this paper and should be further investigated in future research.

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APPENDIX

The Probabilities of Solution Production for Each Item for the Separate Stimulus Words and for the Two-Stimulus Problems in the Explicit-Search Task

Item	T = 60 sec			T = 8 sec		
	$P_{1,T/2}$	$P_{2,T/2}$	Observed	$P_{1,T/2}$	$P_{2,T/2}$	Observed
01	.81	.50	.93	.56	.38	.87
02	.88	.44	.50	.75	.38	.44
03	.56	.31	.75	.25	.19	.63
04	.31	.25	.75	.19	.06	.63
05	.31	.50	.69	.06	.19	.38
06	.19	.50	.38	.00	.13	.06
07	.19	.25	.75	.00	.00	.38
08	.88	.19	.94	.63	.13	.69
09	.06	.19	.81	.06	.13	.75
10	.56	.69	.94	.00	.38	.88
11	.56	.19	.94	.50	.19	.81
12	.25	.00	.19	.13	.00	.19
13	.94	.63	.94	.81	.44	.69
14	.31	.69	.88	.25	.38	.81
15	.13	.81	.88	.00	.69	.56
16	.06	.44	.69	.00	.31	.50
17	.19	.13	.63	.06	.06	.31
18	.19	.06	.25	.00	.00	.19
19	.56	.00	.50	.13	.00	.25
20	.00	.00	.25	.00	.00	.19
21	.44	.94	1.00	.31	.88	1.00
22	.00	.31	.75	.00	.19	.38
23	.69	.06	.81	.13	.06	.50
24	.13	.63	.88	.13	.50	.81
25	.19	.63	.81	.06	.44	.63
26	.13	.13	.25	.06	.00	.13
27	.06	.00	.38	.00	.00	.19
28	.00	.56	.38	.00	.31	.25
29	.56	.13	.63	.31	.06	.44
30	.13	.31	.25	.06	.19	.25
31	.25	.38	.44	.06	.13	.31
32	1.00	.06	.88	.94	.06	.81
33	.00	.56	.63	.00	.44	.38
34	.87	.50	1.00	.60	.25	1.00
35	.40	.75	1.00	.00	.25	.81
36	.19	.00	.13	.00	.00	.00
37	.13	.19	.06	.13	.06	.06
38	.88	.25	.94	.69	.19	.94
39	.13	.38	.63	.00	.19	.50
40	.69	.69	.75	.19	.44	.63