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Estimating Frequency of Occurrence

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During the week just passed, have there been more sunny or cloudy days where you live? Most people have little trouble answering this question, and many can answer it quite accurately even if they don't live in perpetually sunny climes. Apparently, this is because the frequency of occurrence of events is maintained fairly faithfully in memory. How is this so?

Two classes of models have been investigated as accounts of frequency coding. For one class, the main assumption is that frequency is a separately coded attribute of memory traces (e.g., Underwood, 1969). According to models of this class, the registration of a trace about some event has, as one of its components, a frequency tag that is incremented with successive appearances of the same event. Models within this class differ in the proposed mechanism that is used to accomplish the coding. One possibility is that subjects use an active, effortful, conscious strategy of incrementing internal counters with successive appearances of an event (called the numerical inference hypothesis by Howell, 1973). Another possibility is that a separate frequency attribute is updated automatically when the same event is presented repeatedly (e.g., Hintzman & Stern, 1978 ; Underwood, 1969). In either case, however, information about frequency is kept separate from the remaining event-related memorial material.

Contrast these models with ones in which the key assumption is that frequency is an attribute derived from other aspects of an event's memory trace (see Howell, 1973 , and Hintzman, 1976). According to these models, there is no separate entry about frequency information; instead, frequency judgments can be derived from other information that is stored in memory. The two most frequently discussed models within this class differ on the properties of memory representations that form the basis for frequency judgments. One alternative rests on the assumption that the *strength* of a trace is used as the critical dimension on which frequency judgments are based (see Hintzman, 1976 , and Howell, 1973). The other alternative is that repeated presentations of an event lead to the creation of *multiple* traces, which in turn serve as the basis of later frequency judgments (e.g., Hintzman & Block, 1971 ; Hintzman, Grandy, & Gold, 1981 ; Hintzman, Nozawa, & Irmscher, 1982). Both of these views hinge on the assumption that multiple presentations yield monotonic increases in strength or in the number of traces, either of which could be used as the basis of frequency judgments.

How do we distinguish between these classes of models? Two variables have been the focus of research on this issue. One, the focus of this article, is the depth of the processing to which stimulus material is subjected at the time it is encountered. Before discussing this variable, let us first review research concerned with another variable that is relevant to the distinction between direct and indirect models, the effect of intention to code frequency per se.

Intention to Code Frequency

Consider the predicted effect of focusing subjects' attention on frequency itself by warning them of an upcoming test of this attribute. Such an instruction has no predicted effect according to any members of the class of indirect coding models because according to these models, frequency judgments are derived from aspects of the memory trace that are not themselves direct counts of frequency.

By contrast, according to one type of direct coding model, having subjects pay attention to frequency of occurrence in preparation for an upcoming test should have a beneficial effect. The key assumption of this type of direct coding model is that frequency is coded by an active, effortful process, such as counting, that registers and updates a stored frequency attribute. This model predicts that instructions to attend to frequency per se should promote more attention paid to the process that registers information about this attribute, with the potential consequence that frequency will be registered with more fidelity. Of course, all direct coding models need not be bound by this prediction. In particular, a direct coding model in which frequency is registered by an automatic mechanism (e.g., Hasher & Zacks, 1979) need not predict that intention to code frequency will help the operation of this mechanism. Nonetheless, the intention variable may have consequences for frequency judgments according to at least some versions of a direct coding model, in contrast to the prediction for indirect coding models.

Is there an effect of intention to code frequency? Research has been mixed on the effect of instructing subjects about an upcoming frequency test. Some investigators have found no effect at all of this manipulation in experiments in which instructions about an upcoming frequency test were compared to instructions about a general memory test (e.g., Flexser & Bower, 1975 ; Howell, 1973). So there is at least some indication that a set for a test of frequency has little effect on performance. According to the foregoing arguments, this may lead one to have less confidence in some versions of direct coding models as accounts of frequency judgments.

The contradictory evidence comes from three articles in which effects of intentional instructions have been reported (Fisk & Schneider, 1984 ; Greene, 1984 ; Zacks, Hasher, & Sanft, 1982). Of course, under some conditions (e.g., having only a few events to count, having them presented over a short period of time, and having little interference with memory for these counts), knowing of an upcoming frequency test might cause subjects to adopt an explicit counting strategy that is successful.

The experiment by Zacks et al. (1982) may meet some of these criteria. They reported a small effect of counting instructions on subjects' accuracy in judging the frequency of presented words (their Experiment 2). As the authors themselves recognized, the small magnitude of their effect could have resulted from subjects tracking frequency counts consciously for a very small number of stimuli during presentation. Furthermore, there was no interfering task presented between the presentation of the words and the frequency test. Thus, if a count were being kept for a few words, there would be little to interfere with memory for the results of this count. As we have pointed out earlier, there is every reason to suppose that subjects could keep active track of frequency under some circumstances, as Zacks et al. (1982) discovered. Nevertheless, there is clear reason to search for a model of frequency coding that goes beyond counting, even given their demonstration of a counting effect: Although a counting strategy helped their subjects, it was obviously not necessary to the accurate storage of frequency information. Their subjects, and those of many other experiments in which counting would not have been a feasible alternative, were still quite accurate when not instructed to use a counting strategy. So much so that Zacks et al. (1982) largely ignored the small effect of counting that they obtained.

Of more relevance to the models under discussion is a pair of experiments by Greene (1984) . In his first experiment, Greene found that intentional instructions produced more accurate frequency judgments than did incidental instructions. In his second experiment, the author reports that under either of two instructions specifying different levels of processing for a set of stimulus words, a set for a frequency test resulted in more accurate judgments than did no such set. Naveh-Benjamin and Jonides (1986) have discussed some methodological issues that may compromise the relevance of this result for a direct coding model. Nonetheless, the data of Greene (1984) do provide some suggestion of an effect of intention on frequency judgments (see also Greene, 1986).

This result is further supported by the work of Fisk and Schneider (1984) , who had subjects judge the frequency of occurrence of words that appeared during the course of a visual search task. In one condition, they told subjects explicitly that they would be tested on the frequency of the words after the visual search trials were completed. A comparison of frequency judgments in this condition with those that were made under conditions in which subjects ignored the words shows that intention to code frequency has a marked effect. Although Fisk and Schneider (1984) did not clearly separate the effects of coding strategy from intention to code frequency, their data certainly leave the impression that intention has some effect.

Why is there conflicting evidence about the effect of intention? One possibility was explored in an experiment reported by us previously (Naveh-Benjamin & Jonides, 1986). In this experiment we demonstrated that intention does have an effect when the time to code the stimuli is brief, but that the effect disappears under relatively relaxed timing conditions. Therefore, the question of whether intention to code frequency has an effect on later frequency estimates appears to have a mixed answer. As such, the implication for a direct coding model is also mixed. Perhaps some conditions of stimulus presentation and subject strategy promote the use of a direct method of coding frequency, whereas others do not.

Level of Processing

Having reviewed the effect of intention, let us now return to the other sort of instructional manipulation that is of interest with respect to direct and indirect models: the characteristics of memory traces that are created during presentation of a list of items. If frequency judgments are derived from characteristics of the memory traces stored during list presentation, as suggested by indirect models, then variables that affect these traces should affect frequency judgments. One such variable is instruction about the level of processing that should be applied to items in a list. Ample documentation exists that semantic coding of list items leads to better recall than does coding that is tied to some physical aspect of the stimuli (Craik & Lockhart, 1972). If the effect of this difference in coding is lodged in the durability of the traces themselves, and if the durability of traces has an impact on their later judged frequency, as claimed by indirect coding models, then level of processing should have an effect on frequency judgments.

In fact, there is evidence in the literature of just such an effect (Fisk & Schneider, 1984 ; Greene, 1984 ; Rose, 1980 ; Rose & Rowe, 1976 ; Rowe, 1974 ; Rowe & Rose, 1977 ; Naveh-Benjamin & Jonides, 1986 ; also see Naveh-Benjamin & Jonides, 1985 , for supporting evidence from a very different paradigm). As an example, the articles by Rowe and Rose provide ample documentation of such an effect. Rowe (1974) found that instructions to attend to the number of consonants and syllables in each word of a series led to worse frequency judgments for those words than instructions to attend to a semantic feature of the words. The judgments in the former condition were more deviant from the actual frequencies in absolute magnitude, and they were not as discriminant among the actual frequencies that had been presented.

Another example of the effect of levels of processing is found in the report of Rose and Rowe (1976) . They had subjects code words according to either graphemic, acoustic, or semantic dimensions prior to estimating the frequency of presentation of these words. Instructions to pay attention to graphemic features of words led to poorer estimates of frequency than instructions to attend to acoustic or semantic features under conditions in which subjects did not expect a later test of frequency. The inferiority of the graphemic condition was particularly evident in the extent to which the frequency estimates discriminated among the actual frequencies that had been presented.

Overall, then, there seems to be ample reason to suspect that the strategy that subjects use to create codes for words has an important effect on their later judgments of frequency for those words, even when subjects have no explicit reason to code frequency. Such an effect, if robust, has important implications for models of frequency coding because it undermines the central assumption of direct coding models. Coding strategy, as it is influenced by different levels of processing, should not have any obvious impact on the creation of any direct codes for frequency of occurrence, yet, apparently, it has an effect on frequency judgments. The implication is that there may be some indirect way in which subjects arrive at frequency judgments, a way that makes reference to a nonfrequency code that can be influenced by instructions about levels of processing.

The following experiments are concerned with replicating the effect of level of processing on frequency judgments and exploring several accounts of the cause for this effect. If the influence of processing level on frequency judgments implicates an indirect model, then an examination of the nature of the indirect coding is warranted. We begin with a replication of the basic effect.

Experiment 1

Method

Design

The experiment consisted of two phases. During the first phase, subjects were presented with a list of words and asked to write down an associate for each. The critical variable in the experiment was the kind of associate that was to be generated: Half of the subjects were to provide an acoustic associate (a rhyme) for each word, whereas the other half were to provide a semantic associate (a word related in meaning). Subjects were led to believe that a new set of association norms was being created for another purpose, an instruction designed to influence them to pay attention to the task of generating associates. In addition, subjects were told that they would later be tested on the frequency with which each of the words had occurred. In previous experimentation under nearly identical conditions, we have found that such an intentional learning instruction results in frequency judgments that are essentially indistinguishable from judgments produced when subjects have no reason to expect an upcoming test of frequency (Naveh-Benjamin & Jonides, 1986).

The second phase of the experiment consisted of a frequency test given to all subjects in both groups.

Subjects

The subjects were 60 undergraduate students at Ben-Gurion University of the Negev, half of whom participated as a curriculum requirement. The other half were paid for their participation.

Materials and apparatus

The pool of words used in constructing the stimulus list for the first phase of the experiment consisted of 30 high-frequency (greater than 50 occurrences per million) one- or two-syllable Hebrew words (Balgur, 1968). Five of these words appeared once in the list, 5 twice, and so on, so that frequencies varied from 1 through 6. In addition to these 105 stimuli, 3 additional words were added to the beginning of the list and 3 to the end to absorb primacy and recency effects, respectively. Also, 4 words were added to the beginning for practice. Altogether, then, there were 115 words in the stimulus list for the first phase of the experiment. These words were presented sequentially by slide projector. There were several orders of words, all of which were random with the constraints that repetitions of a word were separated by at least 4 other words, and that the repeated words appeared equally in the two halves of the list.

Procedure

There were two groups of 30 subjects each, tested in small subgroups of 5 to 8. In the first phase of the experiment, instructions to each group were appropriate to the design outlined above, with subjects instructed to provide one associate for each stimulus word. All subjects were told that words might be repeated, and that they should attempt to generate a different associate at the time of a word's reappearance if possible. Stimuli during this phase were presented at a rate of one word every 5 s. Each subject had a booklet in which to write the associates, 10 associates on each page. Following the last word of the list, the experimenter engaged subjects in approximately 2 min of conversation before the second phase of the experiment began.

The second phase consisted of a frequency test. There were 35 words on this test: the 30 words presented in the first phase as test stimuli and 5 distractor words that met the same criteria as the 30, but that had not been presented during the first phase. These 35 words were randomly intermixed. Subjects were given a sheet with these words and were asked to provide a numeral from 0 to 6 for each word. This value was to represent the judged frequency of that word during the first phase of the experiment. Subjects were told explicitly that some of the words on the frequency test had not appeared during the first phase.

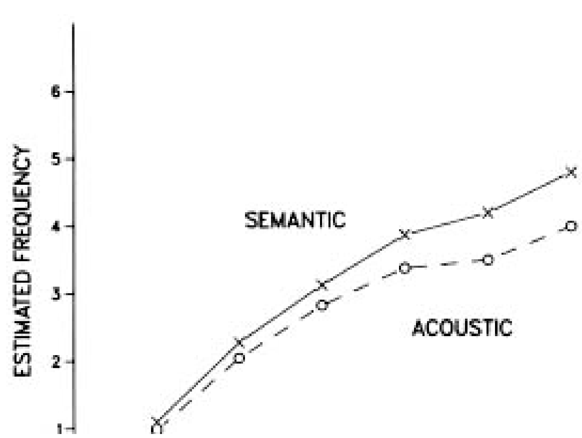
Results and Discussion

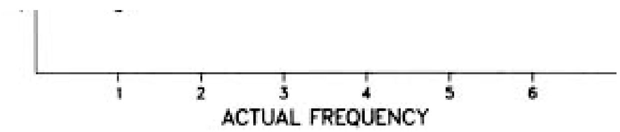
As we have previously argued (Naveh-Benjamin & Jonides, 1986), a complete analysis of frequency judgments requires examination of three pieces of information about the relation between judged and actual frequencies (assuming, as is typical, that the relation between estimated and actual frequency is linear, or nearly so). One is the absolute magnitude of the judgments compared with the actual frequencies. This measure reveals whether subjects are sensitive to the range of frequencies that were actually presented and whether their judgments of frequency tend to underestimate or overestimate the actual frequencies. Also, of course, it is of value to compare these absolute magnitudes between experimental conditions.

A second measure of importance is the slope of the function relating estimates to actual frequencies. This slope is an indicator of sensitivity to variations in frequency. As the slope comes closer and closer to unity, one can conclude that subjects are more and more sensitive to variations in presented frequency.

A third measure of interest is the deviation of each judgment from the mean judgment for a given presentation frequency. Larger deviations obviously imply less consistency in judgments, and therefore less reliability.

The frequency estimates themselves are presented in





Estimated versus actual frequency of occurrence for the semantic and acoustic conditions of Experiment 1.

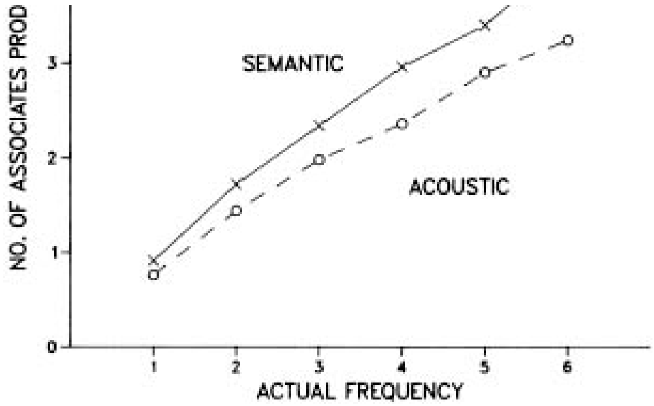
Figure 1 as a function of actual frequency. There were 30 frequency estimates provided by each subject for words that had actually been presented during phase one of the experiment. Five of these were for words that appeared once, 5 for words that appeared twice, and so on. For each subject, the mean estimate was determined for each of the actual frequencies from 1 through 6. These means were then averaged over subjects within each of the two conditions of the experiment. Figure 1 shows clearly that subjects are quite good at estimating frequency in the sense that their judgments are, on the average, monotonically related to the actual frequencies on which they are based. It is also obvious from the figure that there are differences in performance between conditions.

In order to examine these differences, the data that contribute to Figure 1 were first subjected to an analysis of variance (ANOVA) including the factors of acoustic versus semantic encoding, and frequency (1-6). A criterion significance level of $p < .05$ was used for this and all other analyses in this report. The results of this analysis confirmed the picture that emerges from the figure: There was obviously a very reliable effect of frequency, $F(5{,}290) = 800.1$, $MS_e = 0.20$; there was a main effect of coding strategy, $F(1{,}58) = 11.5$, $MS_e = 0.92$; and there was a significant Frequency × Coding Strategy interaction, $F(5{,}290) = 2.80$, $MS_e = 0.20$. This analysis reveals that the semantic condition resulted in frequency judgments of absolutely higher magnitude than those of the acoustic condition. Because most of the estimates in Figure 1 fall below the major diagonal, however, the higher estimates of the semantic condition actually represent less underestimation of the true frequencies.

The interaction that was revealed by the ANOVA indicates that the slope of the function relating judged to actual frequency is higher for the semantic than for the acoustic condition. To confirm this, we linearly regressed each subject's estimates on actual frequency and then compared the average slopes of these functions for the two conditions. The slope for the semantic condition was 0.73, and that for the acoustic condition was 0.64. A t test revealed that these differed reliably, $t(58) = 2.01$. Thus, the semantic condition apparently yields estimates that more faithfully reflect the actual frequencies than does the acoustic condition.

The last analysis of these data concerned the consistency of subjects' estimates in the two conditions. This was assessed by calculating a standard deviation of the estimates for each actual frequency on a subject-by-subject basis. These standard deviations were then averaged across the actual frequencies for each subject to yield one mean standard deviation per subject. The means of these values were 0.92 for the semantic condition and 1.10 for the acoustic condition. These differed reliably, $t(58) = 2.20$.

The preceding analyses show that instructions to produce semantic associations lead to higher, more accurate, and less variable frequency estimates than instructions to produce acoustic associates. Why? Examination of the number of different associates that subjects produce suggests a possible answer.



The number of different associates produced in the semantic and acoustic conditions of Experiment 1.

Figure 2 displays the mean number of different associates produced in the acoustic and semantic conditions as a function of actual frequency. An ANOVA of these data showed that there were more different associations produced in the semantic condition, F (1,58) = 55.6, $MS_e = 2.20$; and there was also a significant Level of Processing × Objective Frequency interaction, F (5,290) = 2.51, $MS_e = 0.40$. Furthermore, examination of the total number of associates generated on each trial by condition, regardless of whether the associates to a word differed from one presentation to another, indicated that there was still a difference in favor of the semantic condition. There were an average of 0.94 associates given in the semantic condition and 0.84 given in the acoustic condition, t (58) = 2.19 .

These association data may bear on frequency judgments in the following way: Suppose that presentation of a word at the time of the frequency test causes one or more associated words to be generated internally. Some of these associations may be recognized as ones that were generated during Phase 1 of the experiment. The number of such associations may then serve, at least in part, as the basis of a frequency judgment that a subject must then provide. If there is nothing familiar about the associations generated internally at the time of test, this could be translated into a judgment of "zero." Similarly, the more different associations that are recognized, the higher could be the judgment given. What we are proposing, in short, is that an indirect coding model of frequency judgments that is based on the number of different associations available at the time of test is a plausible account of the data in Experiment 1. An indirect coding model based on the strength of the traces may also be a candidate explanation if one assumes that the number of associations given by subjects during the presentation phase is reflective of the strength of the trace for the target word. However, later in this article, we present data that cast doubt on the currency of a strength view, as have Hintzman and Block (1971) .

Another class of models assumes a direct coding of frequency. These models cannot readily explain the effect of level of processing that we have documented because this variable should have no obvious influence on a direct frequency code.

A multiple-trace model is well equipped to explain the major effects that we found in this experiment: There were more different semantic associates generated than acoustic associates, which would result in higher estimates of frequency in the semantic condition. Also, because there were both more different associates and more total associates available to serve as the basis of frequency judgments in the semantic condition, subjects had a greater range of associates as a function of actual frequency, which could lead to more accurate estimates as well (as reflected in the slopes). Finally, the greater range of associates might have led to less variable judgments, frequency by frequency, in the semantic condition because the calibration of associates on actual frequency could be more faithful.

According to this model, then, the effect of level of processing in the present experiment is a result not necessarily attributable to the difference in coding per se. Instead, it is that the semantic instructions result in more associations being given. These associations serve as the basis of the frequency judgments that are given for a word. Subjects retrieve associations for a word at the time of the frequency test and use these as the basis for an estimate of frequency.

Before pressing on with this model, we must consider an artifact that may have had an impact on the present results. Suppose that the effect of level of processing was merely to cause subjects to spend more time coding the words in the semantic compared to the acoustic condition. If this were so, greater coding time in the semantic condition could have led to the production of more associates and to better estimation of frequency, according to an indirect coding model. Or, according to a direct coding model, greater coding time in the semantic condition could have led to better rehearsal of the frequency code for the words.

We tested the possibility that greater coding time may enhance frequency estimates by rerunning the present experiment in a self-paced manner (i.e., subjects paced the presentation of slides in both conditions). This procedure led to a much greater presentation time for the acoustic condition as expected, because it is generally more difficult to generate acoustic associates. Yet the overall pattern of results for the frequency estimates was quite similar to the pattern of Experiment 1. Thus, we are confident that a confound attributable to coding time is not an appropriate account of the effect of levels of processing. Also, this result militates against a strength model to account for frequency estimates because such a model would have predicted better estimates for the words in the acoustic condition, assuming a positive correlation between encoding time (which was greater in the acoustic condition) and strength.

Experiment 2

The principal assumption of the multiple-trace model under consideration is that retrieval of associates at the time of the frequency test serves as the basis of judgments. According to this assumption, the more associates that subjects can recall, the higher will be their frequency estimate for a particular target word. Experiment 2 was designed to test this assumption about the relation between recall of associates and generation of frequency estimates.

Method

Design

The experiment consisted of three phases. In Phase 1, subjects were presented with a slide sequence on which target words were presented at frequencies varying from 1 to 6. On each slide, a strong semantic associate of the target word on that slide was presented along with it. Each repetition of a target word had a different associate presented with it. After presentation of the slides, subjects were asked to estimate the frequency of presentation of the target words (Phase 2). Following this, subjects attempted to recall the associates that had been presented with each target word (Phase 3). The main analysis of interest inquired about the relation between the number of associates recalled for each target word and the frequency estimates for that word. The design of the experiment also included a control condition in which subjects recalled the associates that had been presented, without previously having given frequency estimates. This condition was included to determine whether providing frequency estimates prior to recall contaminated the differential recall of associates as a function of actual frequency of presentation.

Subjects

The subjects were 40 students at the University of Michigan who were paid for participation in the experiment. Of those, 21 were assigned to the experimental condition and 19 to the control condition.

Apparatus

A slide projector was used to present the series of words in phase one of the experiment at the rate of one slide every 5 s.

Materials

A total of 48 words were selected as the target words for both conditions of the experiment. For each of these target words, a set of strong associates was selected from the norms of Palermo and Jenkins (1964) . The associates were selected by two judges after a population of potential associates had been selected from the most frequent associates provided in the norms. Of the target words, 8 were presented once during Phase 1 of the experiment, 8 of the words twice, 8 three times, and so on. Each presentation of a word was accompanied by the presentation of a different associate, directly below the target word on the slide. No associate was repeated during the experimental session. Thus, a word presented five times, for example, had five different associates presented along with it. The 168 slides for each condition that resulted from this procedure were randomly arranged. They were preceded by 4 slides to absorb primacy effects, and followed by another 4 slides to absorb recency effects.

The answer sheet for Phase 2 of the experiment consisted of a random arrangement of the 48 target words plus an additional 24 words that served as distractors.

The answer sheet for Phase 3 consisted of a sheet on which were printed the 48 target words in random order. Next to each word were six blank spaces in which subjects were to enter their recall of associates.

Procedure

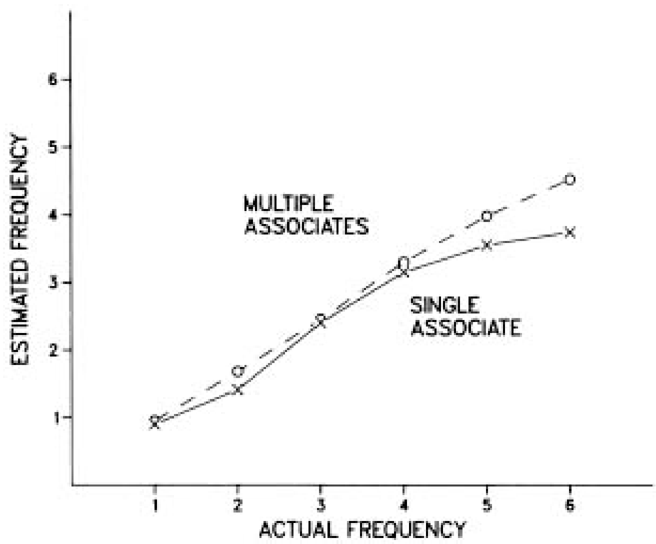
Prior to Phase 1, subjects were told that they would be presented with a series of slides on each of which were two words. They were told that the top word on each slide was the one whose frequency would be tested later on. Also, they were told that the bottom word on each slide was an associate of the top word and was presented to help them remember the target words. The instruction indicated that paying some attention to the associates would likely help subjects remember the frequency of the target words.

The instructions for the experimental condition in Phase 2 were similar to the instructions in the previous experiments. Subjects were told of the actual frequencies that had been used in Phase 1, and they were told that some of the words on the answer sheet had not appeared at all in Phase 1. Finally, they were instructed to enter a number from 0 to 6 next to each word corresponding to their estimate of that word's frequency of appearance. Subjects in the control condition did not engage in this task.

For Phase 3, all subjects in both conditions were provided each of the 48 target words and were asked to recall the associates that had been presented in Phase 1. Because all of the words on the answer sheet for this phase had six blank spaces next to them, subjects could not tell from the answer sheet alone what the frequency of presentation had been for each target word.

Results and Discussion

The frequency estimates of subjects in the experimental condition were 0.96, 1.51, 2.36, 2.97, 3.89, and 4.48 for frequencies of 1-6 respectively. These estimates are quite similar to those generated by the semantic condition in Experiment 1, and they also resemble the estimates that will be described for a similar condition in Experiment 3 (see



Estimated versus actual frequency of occurrence for the single-and multiple-associates conditions of Experiment 3.

Figure 3). The slope of the function for the present estimates was 0.72, and the standard deviation of the estimates overall was 1.07. These values are also comparable to the data from the other experiments. In short, these estimates appear to be representative of frequency judgments that we have obtained in other experiments.

The performance of subjects in recalling associates was as follows: For the experimental condition, subjects recalled 0.28, 0.48, 0.68, 1.06, 1.28, and 1.61 associates for frequencies of 1-6, respectively. The corresponding figures for the control condition were 0.46, 0.71, 1.07, 1.40, 1.51, and 2.06. An ANOVA of these data revealed that there was a reliable difference in the recall performance of the two groups favoring the control condition, $F(1,38) = 4.58$, $MS_e = 1.21$. Also, of course, there was a reliable effect of presentation frequency, $F(5,190) = 123.81$, $MS_e = 0.09$. However, there was no reliable interaction between condition and frequency, $F(5,190) = 1.16$, $MS_e = 0.09$.

The absence of a significant interaction between frequency and condition in this experiment allowed us to examine the relation between success of recall and frequency estimation for the experimental group. Had there been a reliable interaction, this would have suggested that the frequency estimation task, which occurred before recall for this group, somehow had an impact on the success with which subjects could recall associates of words that had been presented with different frequencies. The lack of interaction allowed us to be confident that this was not an issue. The fact that there was a main effect of condition on recall does not compromise our analyses of the relation between recall and frequency estimates. It could well be, for instance, that the control group was slightly more successful in recall because they did not have a filled interlude between presentation of words in Phase 1 and their recall, as did the experimental group. That this could have resulted in a somewhat higher level of recall is not surprising. Of importance is that it did not result in differential recall for the different frequencies compared to the experimental condition.

Because this was so, we turned to an analysis of the relation between frequency estimates for target words and recall of associates for those target words. The version of a multiple-trace model that we have been entertaining asserts that frequency estimates are, at least in part, generated by way of subjects' recalling associates and assigning a frequency estimate on the basis of the number of associates generated. If this is so, there should have been a strong correlation between frequency estimates and the number of associates recalled, and there was. The mean Pearson r was .56. (This is the average correlation coefficient across subjects; for each subject, the mean frequency estimate for each actual frequency was correlated with the mean number of recalled associates for each actual frequency.)

Of course, this correlation could have been spurious. It could have been due to separate correlations between actual frequency and estimated frequency on the one hand, and actual frequency and recall on the other hand. These two correlations, if strong, could have resulted in a spurious correlation between recall and frequency estimates (cf. Shedler, Jonides, & Manis, 1985). To assess this possibility, we calculated partial correlations for each of the 21 subjects in the experimental condition. These partial correlations represent the correlation of estimated frequency with actual frequency, partialing out the effect of associates. If the correlation between recall of associates and frequency estimates was spurious, the partial correlations should be no different than the simple correlations between these variables. That is, if frequency estimates were not at least in part due to subjects' reliance on the number of associates that they could recall, then there should be no change in the correlation between actual and estimated frequency if we controlled for the number of associates recalled; however, there was.

The average partial correlation over the 21 subjects was .59. This value was significantly different from the average simple correlation of .71, as determined by a t test on the Fisher r -to- z transformed scores, $t(20) = 8.15$. In fact, the difference was reliable for 9 of the 21 subjects individually by a one-tailed test, with all subjects showing some trend for the partial correlation to be at least somewhat lower than the simple correlation. Thus, some portion of the correlation between actual and estimated frequency is, in fact, a result of recall of associates, and the subsequent use of this recall as the basis of frequency judgments.

An analysis similar to this one can be conducted on the data of Experiment 1 as well. In that experiment, we did not have a measure of the number of associates that subjects could recall; however, we did have a measure of the number of associates generated at the time of stimulus presentation. Presumably, the more associates generated, the more opportunity subjects have to recall associates later on to serve as the basis of frequency estimates. Thus, a multiple-trace model predicts that a result similar to that of Experiment 2 should obtain for the data of Experiment 1 as well. In Experiment 1, the mean simple correlation between estimated and actual frequency was .75. The partial correlation between these variables, partialing out the number of different associates generated, was .55. These two values were significantly different by a t test on the z -score transformed correlations, $t(59) = 9.67$. As in Experiment 2, then, we propose that subjects in Experiment 1 used their memory of associates (as estimated by the number that they originally generated) as the basis for their frequency estimates, at least in part.

The results of these correlational analyses lend plausibility to the multiple-trace view of frequency judgments. They establish that one route used by subjects to arrive at frequency estimates is by the memorability of words that were associated with the target words at the time the targets were originally presented. This route clearly leads to an indirect estimation of frequency in that the estimates are based, at least in part, on characteristics of the memory traces of the target words, memory traces that are not themselves direct codes for frequency. Of course, this is not the only route. The fact that there remains a quite substantial correlation between estimated and actual frequency even when memory for associates is partialed out (.55 in Experiment 1 and .59 in Experiment 2) means that there is much more to the generation of frequency estimates than simply recalling associates. We address this issue in Experiment 3.

Experiment 3

The results of Experiment 2 make more plausible the proposed model of frequency judgments that was implicated by the effect of levels of processing in Experiment 1. This model postulates that subjects mediate their frequency judgments by reference to their memory of associations given when the words are originally presented. This model, of course, belongs to the class of indirect coding models because frequency judgments are assumed to be derived from an attribute of the memory trace of an item that is not a direct code of frequency itself.

The evidence that we have amassed for this model in the previous experiments is correlational in nature. To provide some directly experimental support for the model, we conducted another experiment in which we directly manipulated the number of different associations available as the potential basis for frequency judgments. If the indirect coding model has currency, then a direct manipulation of the number of different associations available to serve as the basis of frequency judgments should have an effect on performance similar to the manipulation of level of processing that had effects in both Experiments 1 and 2. That is, the more different associations that are available, the better judgments of frequency of occurrence should be. To test this prediction, we conducted an experiment in which we either repeated the same association to a target word as it was repeated or presented a different association each time we presented the target. All associations were of a semantically related sort so that level of processing did not differ between conditions.

Let us review the predictions for this manipulation from various models. First, direct coding models would not predict that the number of associations would have any effect at all because this variable should not influence the frequency code that is presumed to be given to words as they are encoded.

Second, an indirect coding model that claims that frequency judgments are based on the strength of a memory trace would predict that repeating a word with the same association each time would increase the strength of that word more than repeating it with a different association on each occasion. With the same association repeated, the word would be more likely to make contact with the same memory trace created on previous repetitions. This should result in an orderly increase in the strength tag for a word with continued repetitions. Pairing repetitions of a word with a different association each time does not provide assurance that the same internal code for the word will be increased in strength.

Finally, as we discussed earlier, an indirect coding model resting on the assumption that frequency judgments are a function of the number of different memory traces associated with a word (i.e., a multiple-trace model) makes yet another prediction. If different associations are provided for a word on its multiple presentations, this will promote the creation of different traces for the word. This should in turn lead to frequency judgments with greater fidelity and consistency and with larger absolute magnitude than if the same association is provided with each presentation.

Method

Design

As in Experiment 1, there were two phases to this experiment. In the first, subjects were presented with a series of slides on each of which there was a target word and an associate to that target. The critical variable was the number of associates provided: Each presentation of a particular target was accompanied by either the same or a different associate. These are called the single- and multiple-associate conditions, respectively, and this variable was manipulated between subjects. The other variable, frequency of occurrence of the target words, was varied within subjects.

The second phase of the experiment consisted of a frequency test of the target words. All subjects were forewarned about this upcoming test.

Subjects

The subjects were 45 undergraduates of Ben-Gurion University of the Negev who participated as part of a curriculum requirement.

Apparatus

During Phase 1, stimuli were shown at the rate of one every 4 s by slide projector. The words were displayed with the target word above its associate on each slide, and subjects were told which word was the target.

Materials

There were 36 target words used in the experiment; these were selected from a pool of 60 words. A total of 48 of the words in this pool were the words used in Experiment 1, and the remaining 12 were additional words selected with the same constraints. A group of 90 judges (students from the same population as the subjects in the main experiment) provided four associates for each of the 60 words in this pool. These associates were then compiled across judges with the frequency of each associate noted. Each word was then screened for its highest associates. If a word had an acceptable set of high associates, it was included in the final set of 36 words used in the experiment proper. Acceptability was determined by agreement between two experimenters: A word was excluded if its associates seemed excessively idiosyncratic or if an associate was highly related to more than one target word.

Two sets of stimulus slides were then prepared. In one set, six words were assigned to each of the six frequencies of 1-6. Each token in this set was paired with a different associate so that if a word was repeated four times, it had four different associates presented with it on the four occasions. These 126 slides (ordered as in Experiment 1) were then preceded by 5 slides of filler words with associates, and followed by five other filler words and associates to absorb primacy and recency effects respectively. In addition, the entire sequence of slides was preceded by a set of 5 practice slides of words and associates appropriate to the condition. Thus, there were 141 slides in the entire sequence. This sequence constituted the stimuli for the multiple-associates condition.

The slides for the single-associate condition were similarly constructed except that if a word was repeated in the sequence, the same associate was presented on each repetition.

Procedure

Subjects were shown the slide sequence appropriate to their condition in Phase 1. There were 22 subjects in the multiple-associates condition and 23 subjects in the single-associate condition. During this phase subjects were told that paying attention to the associates should help them remember the frequencies of the target words in preparation for the upcoming frequency test. Following presentation of the slides, subjects were given a frequency test with the 36 target words plus six distractor words shown in random order. They were told to assign each word a value of 0 to 6 as an indication of judged frequency.

Results and Discussion

As in the previous experiments, we present the results of three analyses of the frequency judgments. The judgments themselves are presented in Figure 3 plotted as a function of the actual frequencies of the words, with the two conditions presented separately. An analysis of these judgments revealed what is suggested by examination of the figure: There was an obvious effect of frequency, $F(5,215) = 311.1$, $MS_e = 0.36$, and the multiple-associates condition yielded higher judgments of frequency than did the single-associate condition, $F(1,43) = 4.26$, $MS_e = 1.22$. Because the judgments were generally underestimates of the actual frequencies, the higher magnitude of judgments in the multiple-associates condition indicated more accurate judgments overall. The Frequency × Condition interaction was reliable also, $F(5,215) = 2.50$, $MS_e = 0.36$. [1]

This interaction was further examined by calculating the slopes of the functions shown in Figure 3 . Each subject's estimates were linearly regressed on the actual frequencies, and a slope estimate was obtained, subject by subject. These slopes were then compared between conditions. Once again, the multiple-associates condition yielded more accurate judgments as indicated by higher slopes (0.70 vs. 0.59 for multiple- versus single-associate conditions respectively), $t(43) = 2.15$.

Finally, we analyzed the variability of the judgments by computing standard deviations for the judgments of each subject. Subjects in the multiple-associate condition showed less variability in their judgments than did subjects in the single-associate condition (1.07 vs. 1.33 respectively), $t(43) = 2.63$.

These three analyses are quite consistent in showing an effect of the number of associations. This effect is precisely that predicted by an indirect coding model of frequency in which judgments are based, at least in part, on the number of traces stored in memory for a particular word. Let's examine each of these three measures to determine the explanation for each result that is proposed by a multiple-trace model.

The model's principal claim is that frequency estimates are mediated by the number of distinct memory traces for a word that are retrieved at the time of test. Different associations paired with each presentation of a word should enhance the distinctiveness of the memory traces for that word. So, for any given frequency, subjects should be able to identify more different traces to serve as the basis of frequency estimates when each presentation of a word is accompanied by a different associate. Thus, the model accounts for the absolutely higher estimates in the multiple-associates condition.

A multiple-trace model is also compatible with the effect of single versus multiple associates on the slopes of the estimation functions. If there are more distinctive traces available to serve as the basis of judgments in the multiple-associates condition, there is greater opportunity for subjects to calibrate their judgments on number of associations.

Finally, we can also account for the effect of condition on the variability of judgments. The argument here hinges on the number of identifiable traces available after some forgetting has occurred. We assume that the less distinctive traces of the single-associate condition will become less recognizably distinct than those of the multiple-associates condition. Consequently, subjects may be forced to guess from the entire range of possible frequencies, which could lead to higher variance in their judgments.

The effect of multiple versus single associations that we have obtained is somewhat at variance with other reports in the literature concerning variability in encoding and its effect on frequency judgments. Rowe (1974) has reported no effect of variability in the print used for presentation of words, but he has also reported that variability in semantic context at the time of encoding produced lower frequency estimates than a constant context (Rowe, 1973). Likewise, Hintzman and Stern (1978) reported that greater variability in encoding context produced lower frequency judgments than did a stable context. Why do our results show the opposite of this?

We suspect that the differences between our results and previous ones can be traced to the quite different procedures that were used by the different investigators. Rowe's (1973) experiment involved the presentation of homonyms whose repeated presentations were in contexts that referred either to the same meaning of the homonym or to different meanings. It is not particularly surprising that different contexts produced lower estimates, according to a multiple-trace view. The procedure resulted in essentially different words being presented; their only commonality was their orthography. Similarly, but less drastically, the procedure of Hintzman and Stern (1978 , Experiment 1) biased subjects to concentrate on different aspects of a word's meaning on each of its presentations, in addition to using weaker associates of the targets than we used.

Experiment 2 of Hintzman and Stern (1978) may have suffered, in addition, from the influence of subjects' initial recall of the stimuli on their later frequency judgments of these stimuli. Repeated presentation of the same context for a stimulus (famous names in this experiment) may have enhanced recall, and subjects' judgments about frequency may have been based closely on their confidence or success in the recall task. One possible reason for recall to have been superior when the same context was repeated is that the context variation (sentence frames) was inherently not very relevant to the target stimuli, and subjects may not have used the context extensively as an encoding tool. Consequently, variation in the context may not have had a very influential effect on the multiplicity of connections that subjects created to encode the names in memory.

The procedure used in the present experiment avoided some of these problems. The same word was repeated on successive presentations, and the linked associations all made reference to the same sense of the word. That is, only the context varied; the word and the meaning of the word that was the target remained the same.

One might object that our procedure caused words with varying context to command more attention from subjects than words with fixed context. This, in turn, might have led to better encoding of the words with varying context and to better established traces to serve as the basis for later frequency judgments. This may be; however, such an explanation is precisely what we have in mind. The critical element in a multiple-trace view is that there be distinct traces to serve as the basis for later frequency estimates. If these come about through more attention paid to words with different associates, that is a perfectly satisfactory mechanism. The important point is that the multiple traces get established effectively. In concert with the results of Experiments 1 and 2, the present results provide converging evidence that strengthens the case for a multiple-trace view.

Notice that an indirect coding model based on the strength of the trace for a target word is not supported by our data. This model predicts that, if anything, the repeated presentation of the same association with a target word would have strengthened the target word's trace more than the presentation of a different context on each occurrence. We found quite the opposite. Our failure to confirm a strength view of indirect coding is consistent with the report of Hintzman and Block (1971) , whose results are supportive of a multiple-trace view as well.

General Discussion

Let us summarize the results from the three experiments and examine their implications for models of frequency coding. Experiment 1 provides a replication of the finding that semantic processing of words yields frequency judgments that differ from those resulting from more shallow processing. The judgments that result from semantic analysis are more faithfully discriminating among actual frequencies of occurrence, they are less deviant from the actual frequencies in absolute magnitude, and they are less variable. Clearly, depth of processing has a robust effect on frequency judgments.

The beneficial effect of semantic processing for frequency judgments can apparently be traced at least partially to the sheer number of associations that are formed during the semantic analysis. This is revealed in three ways. First, the frequency judgments of Experiment 1 seem to be related to the number of associates that subjects generate during the presentation phase of the words, at least in part. Second, subjects' success in recall of associates that are presented with the target words is related to the magnitude of their frequency estimates, again, at least in part (cf. Experiment 2). Finally, when multiple associates are presented with multiple presentations of a target word, as opposed to repetition of the same associate, there is enhancement of the quality of the ensuing frequency judgments (cf. Experiment 3). For all these reasons, it seems reasonable to conclude that judgments of frequency in these tasks are at least partly mediated by access to memorial traces of associations stored with the target words themselves.

One may wonder about the generality of these findings given our use of a task that included *explicit* associations for the target words. Presumably, if memory traces involving associations play a role more generally in frequency coding and estimation, they do so by use of *implicit* associations. Yet the fact that the present manipulation of levels of processing yielded results quite similar to Greene's (1984 , Experiment 2), which included a quite different manipulation of levels of processing, suggests that we have not done drastic violence to the coding strategies used under less constrained conditions than ours. Similarly, the effect that we report in Experiment 3 is quite similar to the one reported by

Begg, Maxwell, Mitterer, and Harris (1986) . We are confident, therefore, that the present results are of general value in assessing models of frequency coding.

The mechanism that we propose concerning associative connections is, of course, consistent with the view that frequency coding is indirect. By now, many other investigators seem inclined to the same view, and have come to this conclusion from a variety of experimental vantage points, establishing the generality of an indirect model beyond the present task with its use of associations (Hintzman, 1969 , 1976 ; Howell, 1973 ; Hintzman & Block, 1971 ; Hintzman, et al., 1981 ; Hintzman et al., 1982 ; Hintzman & Stern, 1978 ; Jacoby, 1972 ; Tversky & Kahneman, 1973). Furthermore, it is also consistent with the position that the indirect path to frequency estimates is by the number of traces stored, rather than the strength of these traces (See also Hintzman & Block, 1971 ; Hintzman et al., 1982 ; Jacoby, 1972 , for similar conclusions about strength theory.).

But there is obviously more to the story than just this. There is good reason to believe that there is a contribution, possibly a sizable one, of a direct coding mechanism as well. One line of evidence for such a mechanism comes from the work of Shedler et al. (1985) . In one experiment, they had subjects view a set of words that varied in frequency. Subjects then were required to recall the words, engage in a recognition test for the words, and then judge their frequencies of occurrence. Analysis of the results of this experiment showed that the availability of the words following presentation, as indexed by a variety of recall and recognition measures, did indeed account for some of the effect of actual frequency on estimates, as proposed by an indirect coding model, but by far not the largest portion of this effect. Although this result implicates an indirect coding mechanism in part, it disconfirms the hypothesis that this is the only mechanism involved in the coding of frequency. In fact, the results of Shedler et al. suggest that a direct coding mechanism is responsible for more of the variance in frequency estimates than an indirect coding mechanism.

A second result consistent with a direct coding mechanism comes from experiments that have manipulated subjects' intention to code frequency, as reviewed earlier. Intentional instructions do improve frequency judgments under conditions in which there is limited time to encode the target stimulus material (Fisk & Schneider, 1984 ; Naveh-Benjamin & Jonides, 1986). A natural interpretation of these effects is that subjects can choose to create direct frequency codes given the proper experimental conditions.

A third effect that implicates direct coding draws on our analyses of the relation between the number of associations and frequency estimates in both Experiments 1 and 2. In Experiment 1 we found that although partialing out the variance attributable to associations reduced the correlation between actual and estimated frequency, it did not reduce this correlation to zero; most of the correlation between frequency and estimated frequency remained intact. Likewise, a similar analysis for the data of Experiment 2 also revealed a drop in the correlation between true and estimated frequency with number of associates partialed out; but, once again, there was still a substantial relation. Both of these analyses imply that there is a mechanism at work in the coding of frequency that is not dependent on the number of associations generated at the time of stimulus presentation, or on the number that can be recalled later on. A mechanism that coded frequency directly would certainly fit this bill, although there may be other indirect coding mechanisms that would be comfortable with this result as well. (Note that some of the remaining variance in the present partial correlation analyses may be due to the availability of the target words themselves; we measured only the availability of the associates.)

Finally, a direct coding mechanism is also consistent with an often overlooked fact about frequency estimates in many of the tasks that subjects have been given, both in our research and in the work of others. Even under the conditions that yield the poorest frequency estimates, subjects' estimates are still quite good. Reexamine the data from the acoustic condition of our Experiment 1, for example, as presented in Figure 1 . There is obviously a strong relation between estimated and actual frequency for this condition. Similarly, in the incidental learning conditions of Experiment 2 in the report by Naveh-Benjamin and Jonides (1986) , there is still an impressive fidelity to the estimates. These and other results suggest that even under quite demanding conditions, subjects can still produce frequency estimates that are reflective of actual frequency of occurrence, even when they do not intend explicitly to code frequency.

Taken together, all of the results we have discussed indicate that neither an indirect nor a direct coding mechanism is a sufficient account of frequency registration. Rather, we prefer the view that there are multiple mechanisms involved in frequency estimation. Our results and the results of others before us have established that one of these mechanisms is indirect and is very likely based on the existence of multiple traces for words presented on multiple occasions in varying contexts (see Hintzman, 1976 , and Howell, 1973 , for reviews). In addition, there is a contribution of a direct coding mechanism that is not directly dependent on the availability of the memory traces themselves or on associations of these traces. We have previously shown that this mechanism is not completely automatic in character (Naveh-Benjamin & Jonides, 1986). However, it may be substantially similar to a counter for frequency of occurrence, but one that is nonetheless subject to effects of processing capacity and intentional facilitation. Whatever its nature, the mechanism is not of the indirect variety that has been the subject of previous theoretical discussion.

To be sure, this view of frequency coding is not parsimonious. However, it seems to us that the data concerning frequency estimation largely militate against any simple view of the coding mechanism involved. At this point, it seems a reasonable research strategy to investigate the relations among several mechanisms in the coding of frequency information.

Footnotes

1

Note that the interaction of frequency and condition appears to be evident for frequencies of 4, 5, and 6 only. We suspect that this is due to sampling error for one or more of the lower frequencies. In addition, it may be partly attributed to the possibility that our associates were not more closely related to the target words: Begg, Maxwell, Mitterer, and Harris (1986) have shown an interaction between frequency and single versus multiple associates for frequencies of 2 and 3. They also demonstrated that this interaction depended on the degree of relatedness of the target and associated words. Thus, we suspect that an interaction between frequency and single-multiple association conditions is not unique to frequencies of 4 or more.

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