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Short-Term Memory Factors in Ground Controller/Pilot Communication

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Communication between ground controllers and pilots was simulated in a short-term memory task in order to explore sources of memory errors in the air traffic control system. As expected from prior short-term memory research, two major determinants of error probability were (1) amount of information that the pilot has to process in a given time and (2) retention interval between the time information is transmitted from the controller and the time it is acted on (recalled) by the pilot. Additionally, the manner of encoding numerical information was varied. The result of this manipulation indicated that, as suggested by recent research in cognitive psychology, the current information-encoding scheme has substantial room for improvement in terms of minimizing memory failure.

INTRODUCTION

The current air-traffic control system involves a good deal of radio communication between controllers and pilots. Much of this communication consists of messages issued to the pilot by the controller, and the majority of these messages contain numerical information that the pilot must use in some way. Table 1 provides some examples of different types of numerical information contained in messages along with the use the pilot must make of the information.

Personal experience and personal communication with pilots suggests that processing and dealing appropriately with controller-issued instructions may, under some circumstances, place a rather heavy burden on a pilot's memory. Two such circumstances that occur fairly frequently are (1) a controller message that contains more than one instruction (e.g., "fly heading 030 degrees and descend to 3500 feet") and (2) the necessity of performing some kind of distracting activity (e.g., consulting a chart, checking the instruments, putting down a sandwich, etc.) between the time an instruction is issued and the time that the instruction is acted upon.

A Laboratory Analogue of Controller/Pilot Communication

When processing and carrying out instructions issued by a controller, the pilot's principal task is to hold some amount of information in memory for periods of time ranging from 0 to perhaps 20 seconds. A laboratory paradigm that requires a subject to perform a similar sort of task was introduced by Brown (1958) and Peterson and Peterson (1959). Table 2 describes this paradigm and illus-

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TABLE 1

Examples of Types of Messages Involving Numerical Information

Message	
Squawk 7123	Change transponder code to 7123
Contact on 121.3	Change radio frequency to 121.3 megahertz
Descend to 7500	Go down to 7500 feet
Fly heading 275	Change direction so as to end up on a heading of 275°
Altimeter 3004	Set altimeter adjustment to compensate for the fact that barometric pressure is 30.04 inches
Land/taxi Runway 29	Land on/taxi to Runway 29
Except clearance at 40	Stay in a holding pattern until 40 minutes after the hour when further instructions will be issued
Maintain 100 knots	Maintain a speed of at least 100 knots
Wind 080 at 17	Note that wind direction is from 80° at a speed of 17 knots
Cesna 11624, United 279	Aircraft designations

trates the correspondence between it and the pilot's task. In the Brown-Peterson task, each of a series of trials consists of (1) presentation to a subject of some information (e.g., three unrelated letters followed by (2) a variable-length retention interval. At the end of the retention interval, the subject (3) attempts to recall the information that had initially been presented. The subject is required to perform some kind of distracting activity (e.g., counting backward by threes) during the retention interval in order to prevent rehearsal of the to-be-remembered information.

Over the past 15 years, literally hundreds of experiments using the Brown-Peterson paradigm have appeared in the psychological literature. The universal result found in these experiments is that performance is very high at a retention interval of 0 and then declines to some asymptotic level by about 15 seconds. The asymptotic performance level varies both within and between experiments, depending in large part upon manipulations taking place at the time the to-be-remembered information is originally presented.

Two-store theories of memory (e.g., Atkin-

TABLE 2

A Typical Trial in Brown-Peterson Paradigm and the Controller/Pilot Analogue

Brown-Peterson Paradigm	*Controller/Pilot Analogue*
1. Present to-be-remembered information (e.g., BKG)	1. Transmit to-be-acted-on message (e.g., Altimeter 2997)
2. Variable-length retention interval in which subject performs distracting activity (e.g., counting backward by threes) to prevent rehearsal of to-be-remembered information	2. Variable-length of time in which pilot must perform distracting activity (e.g., finishing conversation with passenger) which prevents him from rehearsing or acting on message.
3. Recall signal—subject attempts to recall information	3. Pilot's attention freed and he attempts to recall and act on message (dial 29.97 into altimeter)

son and Shiffrin, 1968; 1970; Glanzer, 1972) ascribe the declining portion of the Brown-Peterson curve to forgetting from a transient repository of information known as short-term store. Asymptotic performance, on the other hand, is assumed to be based on information transferred to a more permanent memory store (long-term store) at the time the stimuli were originally presented.

The present experiment was designed to simulate the pilot's memory task in a controlled, laboratory setting within the context of the Brown-Peterson paradigm. Two types of to-be-remembered messages were used in the experiment: (1a) a place to contact plus (1b) a four-digit radio frequency (e.g., Seattle Approach Control on 121.4) and (2) a four-digit radar transponder code (e.g., 7227). The nature and background of these two types of messages will be discussed in more detail.

Four practically oriented issues were explored in the experiment. The first three involved examination of variables known from past research to affect short-term memory performance. Identification of the magnitude of these effects with the present, aviation-related stimuli will indicate the relative importance of various factors in an actual controller/pilot interaction. The fourth issue involved some preliminary exploration of a relatively uncharted domain: the means by which transmitted information may be encoded optimally so as to minimize errors caused by short-term forgetting.

Forgetting functions. The first issue involved examination of forgetting functions for the two types of information. In particular, it was of interest to determine whether rate of forgetting and/or asymptotic performance level would differ for the various types of information.

Effects of memory load. Past research has suggested that forgetting rate is faster and/or asymptotic performance is lower, the more information the subject is initially given to remember (Melton, 1963; Murdock, 1961). To examine this issue, subjects were, on some trials, given only one message consisting of either one or two pieces of information (i.e., a place/frequency or a transponder code) to remember. On other trials, subjects were given two messages, involving all three kinds of information (i.e., both a place/frequency and a transponder code) to remember.

Sequential effects. A number of experiments using the Brown-Peterson paradigm have suggested that performance on some trial, $n + 1$, may be improved by increasing the time interval between trial $n + 1$ and the preceding trial, n (e.g., Peterson and Gentile, 1965). This effect is examined in the present experiment.

Encoding of transmitted information. The standard practice in the current air-traffic control system is to transmit virtually all types of numerical information in a digit-by-digit fashion. Thus, for example, the radio frequency 118.2 would be transmitted as "one-one-eight-point-two." For convenience of discourse, this type of encoding system is referred to as a *same-encoding system.* An alternate type of encoding system would be to have each type of numerical information encoded in its own unique way. An example of such a *unique-encoding system* would be to encode radio frequencies in the digit-by-digit manner described above but to encode transponder codes as two pairs of double digits (e.g., "7227" would be encoded as "seventy-two, twenty-seven").

Several lines of research suggest that the unique-encoding system would lead to fewer errors than the presently used same-encoding system. Perhaps the most direct evidence comes from a series of studies by Yntema (Yntema and Mueser, 1960; Yntema, 1963). In these studies, subjects had to keep track of the states of several variables (analogous to, for example, the state of a radio frequency and the state of a transponder code). These studies found subjects to be considerably better when each variable had its own unique set of states relative to when the variables had states in common.

In the short-term memory literature, much attention has been paid to the phenomenon of "release from proactive interference." In its broadest sense, "proactive interference" is a label referring to the fact that subjects show little or no short-term forgetting on the first trial of a Brown-Peterson task (Keppel and Underwood, 1962). Likewise, "release from proactive interference" refers to the fact that if, during a Brown-Peterson task, the type of stimulus material is changed from trial n to trial $n + 1$ (e.g., from letters on trial n to digits on trial $n + 1$), then subjects will show a substantial decrease in forgetting on trial $n + 1$. The typical explanations advanced for this phenomenon (e.g., Loftus and Patterson, 1975) involve the following notion. Suppose a subject must remember two pieces of information, A and B, that are presented in close temporal proximity. To the extent that A and B may be differentially encoded, they will be less confusable, and hence easier to recall. Carrying this notion over to the controller/pilot situation, it seems reasonable to expect that two pieces of numerical information will be easier to remember to the extent that they are uniquely encoded.

To test the relative efficacy of the unique as opposed to the same-encoding system, information corresponding to the transponder code was transmitted in one of two ways on different trials in the present experiment. On some trials, the code was transmitted digit-by-digit (e.g., seven-two-two-seven). On other trials, the code was transmitted as two double-digit numbers (e.g., seventy-two, twenty-seven). Radio frequencies were always transmitted digit by digit. The former type of trial, therefore, involves use of a same-encoding system, whereas the latter type of trial involves use of a unique encoding system.

METHOD

Subjects

Four female undergraduates responding to a posted notice served as subjects. All subjects were naive with regard to anything having to do with aviation or with the air-traffic control system. Each subject agreed to participate in 19 30-min sessions and was paid $2 per session.

Stimuli

As noted above, two types of messages were used: (1) a place to contact plus a radio frequency and (2) a transponder code. The means by which these messages were generated are described in some detail below. In order to acquaint the reader with the practical significance of these messages, however, a brief description of how they are incorporated within the air traffic control system is necessary.

Air traffic control. Virtually all commercial flights (as well as many private flights) are made within the context of the air-traffic control system. When within this system, an aircraft is in communication with a series of ground controllers. Which controller an aircraft is in communication with at any given time depends on the current geographical position of the aircraft.

Control entities. For the purposes of the present experiment, a pilot is always assumed to be communicating with one of two *control entities:* a *center* or an *approach control.* The geographical domain of a center is large, generally including several states. The designation of the center is generally the name of a large city situated within the boundaries of the center (e.g., New York Center, Cleveland Center, etc.). The geographical domain of an approach control, on the other hand, consists of a roughly circular area, approximately 80 km in diameter, around a major airport. The designation of an approach control consists either of the name of the airport or of the name of the city in which the airport is located (e.g., Kennedy Approach Control, Boston Approach Control, etc.).

Radio frequencies. Whenever an aircraft moves across a boundary dividing one control entity from another, the aircraft is "handed off" from one controller in the entity being departed to another controller in the entity being entered. For example, an aircraft flying into Boston would, until it was about 40 km from Boston, be under the jurisdiction of Boston Center. Upon crossing a geographical boundary into the jurisdiction of Boston Approach Control, the aircraft would be handed off via an instruction from Boston Center such as "contact Boston Approach Control on 123.1." The pilot would then change his radio frequency to 123.1 and inform Boston Approach Control that he was now on that frequency.

Within a single control entity, there are typically several different radio frequencies used for communicating with aircraft located in different geographical subareas within the domain of the entity. Consequently, a pilot is instructed to change radio frequencies when passing from one subarea to another. The fact that a pilot must change radio frequencies both between and within control entities means that such frequency changes must be carried out fairly often.

Transponder codes. A controller keeps track of aircraft positions by watching "blips" on a radar screen, each blip corresponding to a single aircraft. Many aircraft are equipped with devices called transponders. A transponder recognizes a signal sent out by a radar transmitter on the ground and transmits back (transponds) another signal using any one of 4096 different transponder codes. Typically, the ground controller instructs each aircraft under his jurisdiction to transpond using a different code. A computer on the ground can then sort out the incoming codes and thereby uniquely identify each transponding aircraft on the radar screen. (Such a system greatly simplifies the job of the controller, who otherwise would have to constantly remember the identity of each blip on his screen).

A transponder code consists of a four-digit number, each digit ranging from 0-7 (hence the 8^4 or 4096 separate codes). Due to various exigencies of the air traffic control system, pilots are instructed to switch codes fairly frequently, often in conjunction with a switch in radio frequency. The term used to request a transponder code switch is "squawk"; thus, for example, an instruction to switch transponder code to 7227 would consist of the message, "squawk 7227." (The term "squawk" derives from the fact that a transponder was originally viewed as "parroting back" radar signals, and parrots squawk.)

Generation of stimuli. The actual messages used in the experiment were generated as follows.

(1) Place/frequency messages. Six control entities, three centers, and three approach controls were chosen arbitrarily and were used throughout the experiment. These entities were: Seattle Center, Oakland Center, Salt Lake City Center, Seattle Approach Control, Portland Approach Control, and McChord Approach Control. (McChord is an Air Force base near Seattle). Whenever one of these entities was used in a message, it was paired with a radio frequency. The radio frequency was of the form *abc.d* where $a = 1$ and *b*, *c*, and *d* were randomly chosen digits with the restriction that $1 \leq b \leq 2$. The digits were always read sequentially and included the decimal point. Thus, for example, the pair Seattle Center and 128.9 would be read as "Contact Seattle Center on one-two-eight-point-nine."

(2) Transponder code messages. Information corresponding to a transponder code always consisted of four octal digits. There were two

> methods of presenting the digits which we designate as "chunked" and "sequential." Chunked digits were read as a pair of two-digit numbers. For example, 4273 was presented as forty-two—short pause—seventy-three on chunked trials. On a trial involving sequential presentation, the same transponder code would be presented as "four-two-seven-three." The first and third digits of a transponder code consisted of randomly selected digits from 1 to 7 (inclusive) while the second and fourth digits were chosen from 0 to 7 (inclusive). There were no restrictions on repetition within the four digits.

All stimuli were presented in a female voice over earphones via a tape recorder.

Design and Procedure

Each of the four subjects participated in 19 sessions. The first was a preliminary session in which the subjects were given an explanation of the air-traffic control system and introduced to the procedures of the experiment. The second and third sessions were practice sessions, and the final 16 sessions were experimental sessions.

Each session consisted of 72 Brown-Peterson trials. Each trial consisted of (1) presentation of the message or messages, (2) a variable retention interval during which the subject was required to repeat back rapidly presented random letters, (3) a recall signal, and (4) a 10-s recall period during which the subject attempted to recall the information presented at the start of the trial. Recall was carried out as follows. During the recall period of each trial, the subject was provided with a response sheet bearing the words: "Contact _________ on _________; squawk _________." The subject attempted to fill out the appropriate blanks and then turned the sheet over at the start of the next trial. When more than one kind of information had to be remembered, subjects were permitted to recall in any order; but the order was not recorded.

Several variables were manipulated over trials.

> (1) Retention interval was either 0 s, 5 s, or 15 s.
> (2) The to-be-remembered messages consisted of either a place/frequency, a transponder code, or both. Conditions in which one message versus two messages are to be remembered are referred to as low memory load and high memory load conditions, respectively. On high memory load trials, the place/frequency information always preceded the transponder code information.
> (3) When a transponder code was presented in either a low or a high memory load condition, it was read in either a chunked or a sequential fashion, as described above. Figure 1 shows the manner in which the various conditions resulting from these manipulations were distributed among the 72 trials.

Nineteen tape-recorded sessions were prepared. In each session the various conditions shown in Figure 1 were presented in a random order. Each of the three kinds of stimulus information (place, frequency, and transponder code) was generated randomly whenever it was needed on a trial. The nineteen sessions were presented in a different random order to each subject.

RESULTS

Figure 2 shows the principal results from the study. All the curves in Figure 2 are forgetting curves; that is, they represent proportions of correct responses as functions of retention interval. A response was considered to be correct only if all components of the response were correct. For numerical responses, this means that all digits had to be correct and in proper order. For place responses this means both the city or airport name (e.g., Seattle) and the type of control entity (e.g., Center) had to be correct.

The ten curves in Figure 2 are initially subdivided according to the three dependent variables: probability of a correct response for place (left panel), frequency (middle panel), and transponder code (right panel). In each panel, the curves are further subdivided into those corresponding to low memory load (dashed curves) vs. high memory load (solid

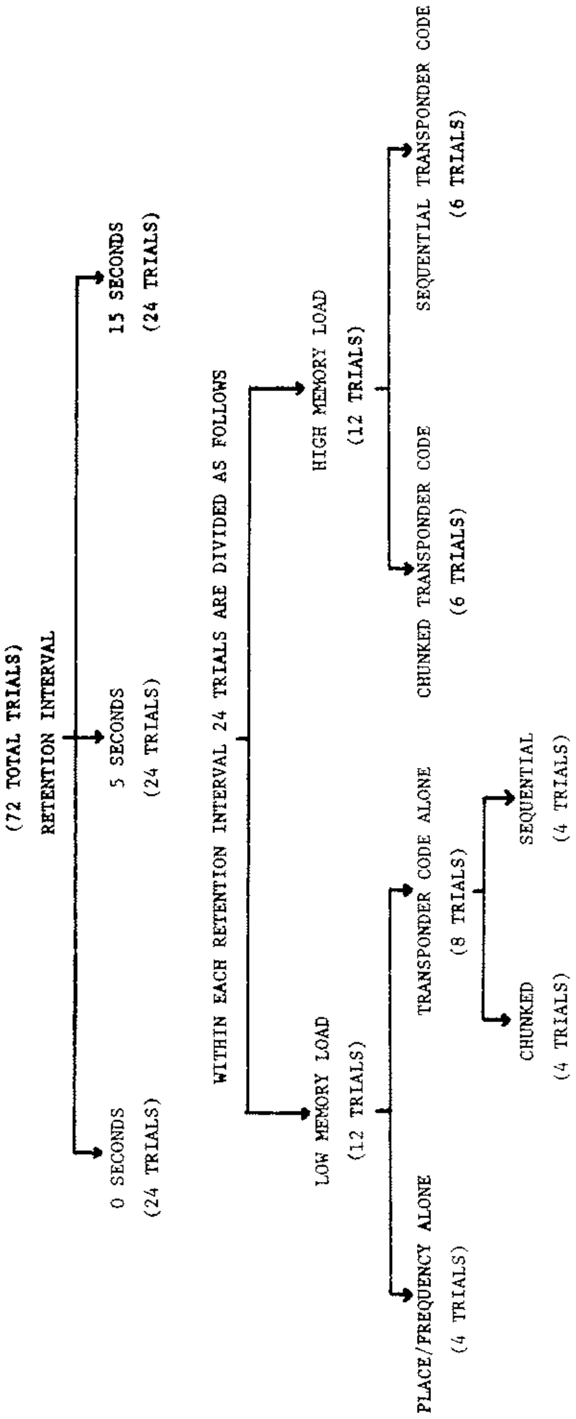

Figure 1. *Distribution of conditions among 72 trials in an experimental session.*

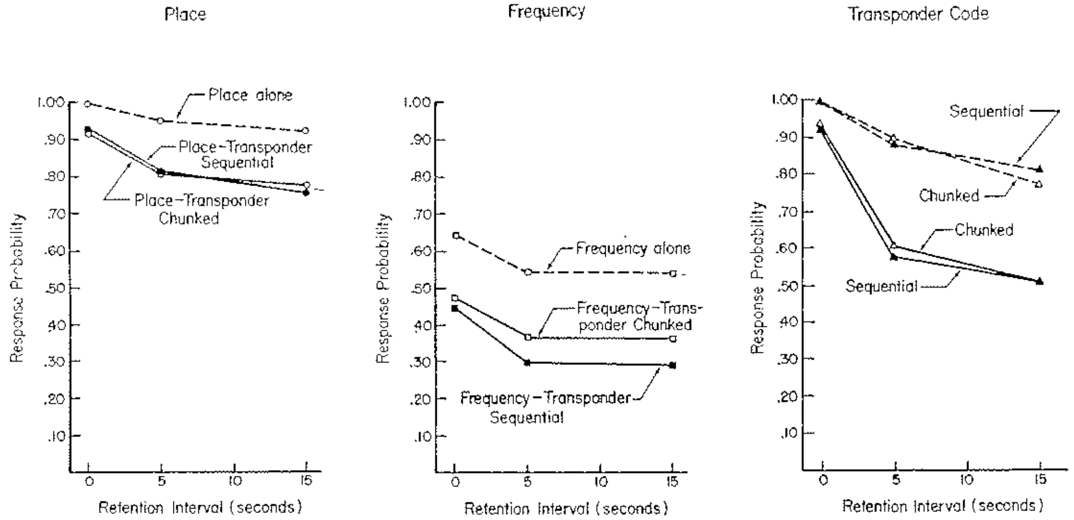

Figure 2. *Forgetting curves for various kinds of information presented in various conditions. (Left-hand panel represents place responses, middle panel represents frequency responses, and right-hand panel represents transponder code responses. Dashed lines represent responses in low-information load conditions, whereas solid lines represent responses in high-information load conditions.)*

curves). Finally, the transponder code curves as well as the high memory load place and frequency curves are subdivided according to whether transponder code was chunked or sequential.

Effects of Major Variables

Several aspects of the data shown in Figure 2 are of interest and require further elaboration. These aspects include (1) forgetting effects, (2) effects of information load, and (3) effects of the chunked/sequential variable.

A series of six analyses of variances (ANOVAs) constitute the principal statistical analyses. One ANOVA was performed for each of the dependent variables in both high and low memory load conditions. All ANOVAs included delay as a factor. Four of the ANOVAs—for transponder code, high and low memory load, as well as place/high memory load and frequency/high memory load—also included the chunked/sequential variable as a factor. In none of the four two-way ANOVAs was the delay × chunked/sequential interaction significant.

Forgetting. Forgetting of place and frequency information is relatively insubstantial in this experiment: the percent decrease in correct responding is on the order of 10-15% over the 15-s retention interval. However, the effects that are observed are generally reliable. For frequency, the delay factor is significant in both the high and low memory load conditions, $F(2, 6) = 5.84$, $p < 0.05$ and $F(2, 6) = 20.88$, $p < 0.05$, respectively. For place, delay is significant in the high memory load condition, $F(2, 6) = 6.15$, $p < 0.05$, but not in the low memory load condition, $F(2, 6) = 4.15$, $p > 0.05$. Of some surprise is the relatively low performance for frequency after the zero-second delay. For example, even when only a place/frequency message is to be remembered, zero-second performance for frequency is only 64%. Immediate memory that is this poor is generally believed to reflect the fact that in many instances information was never registered in short-term store. Both of these findings—relatively slight forgetting and lack of initial storage—are at odds with previous findings that have emerged from the Brown-Peterson paradigm. These apparent anomalies will be discussed in a later section.

The data corresponding to memory for the transponder code are somewhat more in line with prior findings: zero-second performance is relatively high, consistently exceeding 90%. The amount of forgetting, however, while greater than forgetting of place/frequency information, is still only about 20% when the transponder code is presented alone. The effect of delay is significant in both high and low memory load conditions, $F(2, 6) = 11.22, p < 0.05$ and $F(2, 6) = 65.94, p < 0.05$ respectively.

Effect of memory load. The effect on memory of the number of to-be-remembered messages appears to be somewhat different for place/frequency versus transponder code information. As can be seen in the middle panel of Figure 2, the effect on memory for frequency of having to remember additional information seems to be to decrease the zero-second performance without affecting the amount of decrease in performance over retention interval. In contrast, as noted previously, increasing the memory load appears to have relatively little effect on zero-second performance of transponder code information, but the effect of memory load on forgetting rate is quite pronounced.

Effect of chunked versus sequential presentation of transponder code. Of perhaps the greatest interest in the results of Figure 2 is the effect of sequential versus chunked presentation of the transponder code. Recall that these two modes of presentation correspond to a "same-encoding scheme" versus a "unique-encoding scheme," respectively. The same-encoding scheme, currently in use in the air traffic control system, was predicted to lead to poorer performance than the unique-encoding scheme.

As indicated in Figure 2, chunked transponder code presentation does indeed lead to superior performance, but in an odd sort of way it boosts correct responding to frequency information only. The effect of chunked/sequential is significant for the high memory load frequency condition, $F(1, 3) = 25.00, p < 0.05$. However, chunked/sequential is not significant for the high memory load place condition or the high or low memory load transponder conditions, $F(1, 3) = 0.03, p > 0.05$, $F(1, 3) = 3.12, p > 0.05$ and $F(1, 3) = 0.24, p > 0.05$, respectively.

Sequential Effects

Clearly one of the most prominent sources of variation in the data of Figure 2 is the memory load factor; specifically, all types of information are subject to a substantial performance decrease when in a high as opposed to a low memory load condition. To identify the locus of this effect more precisely, an additional analysis was performed. An examination was made of all sequential pairs of trials that had either a place/frequency message only on trial n followed by a transponder code message only on trial $n + 1$ or the reverse—transponder code only on trial n followed by place/frequency only on trial $n + 1$. Response probability on trial $n + 1$ was then determined as a function of trial n retention interval. Due to the problem of relatively small amounts of data, these probabilities were collapsed across trial $n + 1$ retention interval and sequential/chunked.

Figure 3 presents these data. Separate curves are shown for place, frequency, and transponder code responses. As noted, the abscissa represents retention interval on trial n; for comparison purposes, the unconditional probabilities of responding to the three types of information on high memory load trials is shown at the left. Thus, the abscissa represents, in part, a scale of temporal separation between presentation of the two messages, with the far left-hand point corresponding to zero separation.

Two questions were asked in regard to the data in Figure 3. First, for each of the three types of information, was there a difference between performance when the information was presented in a high memory load condition (place/frequency and transponder code all at once) versus performance when a given type of information was presented by itself but just following a trial on which the other type of information had been presented? For each of the three curves in Figure 3, this question was implemented by applying the planned comparison C1 = {−3, 1, 1, 1} to the four means. The second question was: Does trial $n + 1$ performance improve with trial n retention interval? To answer this question, a second comparison, C2 = {0, −1, 0, 1}, was applied to each of the curves in Figure 2. Note that C1 and C2 are orthogonal to one another.

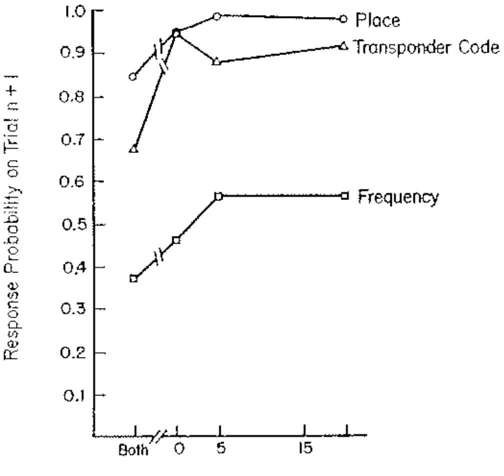

Figure 3. *Data from pairs of successive trials n and n + 1 on which either a place/frequency message was presented on trial n followed by a transponder code message on trial n + 1, or vice-versa. Ordinate is probability of a correct response on trial n + 1 and abscissa is retention interval on trial n. Far left-hand point corresponds to response probabilities on high-information load trials.*

The results of these comparisons are presented in Table 3. For each of the three curves of Figure 3, Table 3 shows (1) the percent of between-conditions variance accounted for by C1, C2, and the residual, and (2) the F-values that indicate whether these percentages of variance differ significantly from zero.

As is clear from Table 3, C1 accounts for a large percentage of the variance and is highly significant for each of the three curves. This indicates that encoding and trying to recall both a place/frequency message and a transponder code message all at once is considerably more difficult than encoding one message, trying to recall that one, and then shortly thereafter, encoding, then trying to recall the other message.

The results of C2 are not so straightforward. For frequency information, C2 is significant and accounts for about 20% of the between-conditions variance. Contrarywise, C2 accounts for only a small amount of variance and is not significant for either place or transponder code information. The tentative conclusion is that memory for the three types of information is affected differently by variation in trial n retention interval. However, since overall response probability is so high for transponder code and place information, the nonsignificance of C2 may merely represent a ceiling effect and must be interpreted very cautiously.

DISCUSSION

Recall Order

As noted above, there are a number of apparent anomalies in the data shown in Figure 2. First, why do the forgetting functions appear to behave so differently for transponder codes as opposed to frequency information

TABLE 3

Results of Two Planned Comparisons for the Three Curves of Figure 3

Source	*% Variance*	*F (1, 9)*
Transponder Code		
C1	96.5	18.56*
C2	1.2	0.22
Residual	2.3	0.44
Place		
C1	94.1	16.0*
C2	3.5	0.6
Residual	2.4	0.4
Frequency		
C1	73.0	73.0*
C2	19.8	20.0*
Residual	6.9	6.9*

*$p < 0.05$

C1 results from application of weights $\{-3, 1, 1, 1\}$.

C2 results from application of weights $\{0, -1, 0, 1\}$.

Residual is variance left over after variance due to C1 and C2 is removed from total, between-conditions variance.

(both are four-digit numbers)? Second, why is the frequency information so low at the zero-second intervals?

A possible explanation may lie in the order in which the various pieces of information were recalled. Suppose that recall of one piece of information (e.g., frequency) did not begin until recall of another piece of information (e.g., transponder code) had taken place. The effective retention interval for this piece of information would then be increased relative to what the retention interval had been defined by the experimenter to be. The forgetting functions shown in Figure 1 would then represent left-truncated pieces of the "real" forgetting functions which would presumably start at 1.0 for a zero-second retention interval. Since recall order was not recorded in the present experiment, this explanation must remain speculative for the time being. Note, however, that the only forgetting function for singly presented information—transponder code presented alone—does begin at 1.0 just as it should.

Practical Implications

As can be seen in Figure 2, there is wide variation in the probability of a correct response to the various types of information over the various conditions—the range of means is from 0.30 to 1.00. This variance is attributable to a number of sources.

Kind of information. Much of the variance appears to be accounted for by what kind of information is being recalled: in general, place information is remembered very well, frequency information is remembered relatively poorly, and memory for transponder code information is in between. However, it is not clear how generalizable this result is; rather, it may be a consequence of the specific experimental paradigm and, in particular, from the orders in which the different kinds of information were presented by the experimenter and recalled by the subject.

Memory load. As expected from the results of prior research (e.g., Murdock, 1961) the number of messages that the subject was required to remember had a fairly large effect on the probability of correctly responding to any particular message. The practical moral—particularly as illustrated by the data shown in Figure 3 and Table 3—is clear. Whenever possible, as little information as is feasible should be conveyed by the controller to the pilot at any one time. In particular, no instruction should be conveyed until 10 s or so after the previous instruction has been acted upon.

Forgetting. The fact that forgetting occurs over an interval of 15 s following the initial reception of a message simply underlines what is intuitively evident to most pilots—that, if at all possible, a message should be responded to as soon as possible after it is received.

Encoding of transmitted information. Although the sequential/chunked variable accounted for a relatively small proportion of the total variance, the finding of an effect of this variable provides a demonstration of potential room for improvement in the presently used system. Hence, this finding has perhaps the most profound implications from a practical standpoint. Attention is traditionally paid to the question of how transmitted information should be encoded so as to minimize errors in perception (e.g., by use of the phonemic alphabet). However, virtually no attention has been paid to the question of how information may be encoded so as to minimize errors in memory. The chunked/sequential variable represents but one possible improvement in encoding of transmitted information. Potentially, there are many others.

Subject Population

The present experiment utilized a limited number of subjects who were naive with respect to air-traffic communication. The decision to use a limited number of subjects stems from the general philosophy that, when examining relatively basic processes, it is better to use few subjects with a large amount of data per subject rather than many subjects with little data per subject. As indicated by the large statistical effects underlying the major conclusions, intersubject variability was quite small in the present experiment. The decision to use naive subjects rather than experienced pilots was a practical one—it was simply not possible to find experienced pilots who were willing to undertake the rather formidable amount of time required for the experiment. But the choice of subject population raises the question of how generalizable the present results are to experienced pilots.

There are three responses to this question. First, each subject participated for a total of almost 1400 trials, and by the time the practice sessions had ended the subject had already participated in 216 trials. Thus the subjects were highly practiced with the stimulus material before the experiment proper began.

The second response is that the majority of private pilots are themselves "naive" in the sense that they have not had vast amount of experience dealing with air-traffic controllers. It is precisely these pilots who have the most difficulty remembering and utilizing air-traffic information because they typically do not have the paraphernalia (writing pads, co-pilots, etc.) that are designed to facilitate communication. It seems reasonable to expect that the results from the present experiment would generalize to this group of pilots.

Finally, the major results of this study were, as noted above, predictable from theories of basic human information processing. It seems unlikely that human beings undergo fundamental changes in their ways of processing information by virtue of their being trained as pilots. It is, of course, possible that experienced pilots would behave differently in the present study than did the naive subjects. This possibility could only be resolved by additional research.

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