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ATTENTION AND WORD RECOGNITION:
EXPLORING THE FUNCTIONAL ARCHITECTURE
OF THE
PARALLEL CODING SYSTEMS MODEL

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ATTENTION AND WORD RECOGNITION: EXPLORING THE FUNCTIONAL ARCHITECTURE OF THE PARALLEL CODING SYSTEMS MODEL

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ABSTRACT

Recent evidence for dual route theories of spelling to sound by Paap & Noel (1991) suggests that attention demand from a memory task performed concurrently with word naming causes a severe slowdown of the orthographic to phonological coding process which causes the naming of low frequency exceptionally spelled words to speed up under memory load despite the fact that naming of other types of words slows down. The locus of the effect which causes this speedup was sought in an experiment on interference while naming words. It was found that neither the effect of attention demand alone nor the effect of assembled phonological-articulatory interference alone would cause the speed up in naming of low frequency exception words. Memory loads which were lexical in nature, digits and high frequency nouns, did provide this type of evidence for a multiple route model of word recognition. Thus the locus of the effect must lie in processes that utilize retrieved rather than assembled phonology or articulation. Single route theories of word recognition and naming could not explain the pattern of results as well as multiple route theories.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I
Introduction

There is more than one way to skin a cat, but is there more than one way to read a word? In the Parallel Coding Systems model of visual word recognition (Carr and Pollatsek, 1985), reading is depicted as a conglomeration of skills rather than as a single process. The idea that the memory representations of a word can be contacted from visual input in more than one way is at the core of the theory. This idea has recently been challenged on two fronts: Evett and Humphreys (1985) and more recently Van Orden, Pennington, and Stone (1990) attack the existing data which support dual route theories and Lukatela and Turvey (in press) present new empirical evidence in favor of a single route theory of spelling to sound. This paper will survey the various approaches that have been taken to modeling the word recognition process and provide new evidence for a multiple route approach to pronouncing written words.

The question of how a word contacts its representation in memory during the process of reading has been complicated of late by the question of whether or not words themselves have dedicated memory representations at all. This debate is not over whether words are represented in memory but over what form that representation takes. Historically, most models of word recognition have adopted a representational scheme for words similar in spirit to Selfridge's pandemonium model (Selfridge, 1959). In Selfridge's model each word in memory has its own dedicated representation, its own node. This notion has been challenged by Parallel Distributed Processing models (Seidenberg and McClelland, 1989) in

which words have no dedicated representations in memory. Words in PDP models are represented as a pattern of activation among a set of word feature representations. This representational scheme challenges the traditional notion of word recognition, in which a word is considered to have been recognized when it has contacted its representation in memory, because words do not have dedicated memory representations in the PDP models. In this paper, the question of how words are represented in memory will not be addressed. The question of interest is: How many routes are there from spelling to sound?

Despite the unusual representational scheme of the PDP models, Seidenberg and McClelland's implemented model has only a single route which information may take from spelling to sound. This single route approach to reading is also taken by models of word recognition which are more conventional than the PDP models, in that they do have dedicated word representations in memory. This class of models is referred to as lexical instance models; in these models, a word is considered to have been recognized when it has contacted its representation in memory. However, lexical instance models neither agree on the nature of the information being contacted in memory nor the routes by which visual information comes to contact its form in memory.

This paper will consist of a review of the architectures of the various models of word recognition and consider what can be learned about the validity of these models by defining the uses to which they put various concepts of "attention." That is, various models of visual word recognition will be reviewed with respect to how they answer two questions: (1) How many routes are there from spelling to sound? and (2) How do these routes employ processing resources? The answers which various models of visual word recognition offer to these questions will be evaluated through the consideration of existing data on attention and visual word recognition along with new data from the experiments reported in this paper.

The model ultimately investigated in this paper, the Parallel Coding Systems model (Carr and Pollatsek, 1985), uses all of the routes to memory which will be discussed and therefore has the greatest explanatory power (However, the model still makes explicit predictions and is therefore falsifiable). The goal of this investigation was not to discover the underlying representation of information but rather the routes which incoming visual information takes in contacting memory traces. This approach may at first seem backwards: How can one investigate the paths information takes in contacting a memory representation whose nature remains unclear? Such an investigation is possible if one views word recognition as a process, a process which takes a certain amount of time and suffers in certain ways from interference. By comparing how the naming of certain types of words suffer from various types of interference, it is believed that differences in the way words are processed will emerge.

Much information could be stored about words, but three types of information stored about a word central to this discussion are: (1) knowledge of its spelling or written form, (2) knowledge of its phonology or pronunciation, and (3) the meaning of the word. The collected representations of this information in memory are referred to as the lexicon, a mental dictionary of sorts. Many models

outlined below place all of the information about a word into a single lexicon but a recent review by Carr and Pollatsek (1985) presents a convincing case for multiple files. That is, the information is split up into a number of separate files. As will be argued later, the conception of the lexicon as consisting of separate files avoids pitfalls experienced by the various single file models.

Because of the uncertainty about the underlying representation of words in memory, it makes no sense to talk about contacting a singular representation in memory, a process called lexical access. This term originated with models having a single lexicon (i.e. Morton, 1969). In the interest of clarity, access will be discussed in terms of the specific type of information being contacted: information about meaning, information about form, or information about pronunciation.

Classifying Models of Word Recognition

Despite differences among the models in the form and existence of the lexicon, it may not be most informative to classify word recognition models according to the number of files in their lexicons. I will adopt the classification scheme which Carr and Pollatsek (1985) choose, which is the classification of models by how the lexicon is accessed. Parallel Distributed Processing models are difficult to classify in this manner as there is not a lexicon to be accessed. However, inasmuch as there is one route from the written form to the memory representation in the implemented Seidenberg and McClelland (1989) model, it represents a single route approach.

The conception that the lexicon consists of a single file which is accessed by one route is shared by logogen models (Morton, 1969; Morton, 1979) and interactive activation models (McClelland and Rumelhart, 1981). In some verification models (Becker, 1976; Herdman and Dobbs, 1989; Kellas, Ferraro and Simpson, 1988) the lexicon consists of one file with a single access route while in other verification models (Paap, Newsome, McDonald, and Schvaneveldt, 1982) the lexicon consists of a single file which can be accessed in more than one way. However, in all of these models, once a word is accessed, all information about that word becomes available. Lexical search models (Taft and Forster, 1975, 1976) also consist of a single lexicon which contains all of the information about a word. Access to the lexicon in lexical search models is indirect in that it is mediated by morphological decomposition, the process of removing affixes and looking up the root in the lexicon. The dual route model of pronunciation (Paap and Noel, 1989; Paap, McDonald, Schvaneveldt and Noel, 1987; Coltheart, 1978) has a single lexicon but pronunciations of visually presented words can be generated in two different ways: First, a pronunciation can be retrieved from the lexicon. Second, a pronunciation can be generated or be assembled by a set of rules. The Parallel Coding Systems (Carr and Pollatsek, 1985) denies the possibility of none of these routes to access. The lexicon of the Parallel Coding Systems (PCS) consists of at least two files: (1) The Phonological Lexicon, which contains information about phonology. (2) The Semantic Lexicon, which contains information about meaning. These two files can each be accessed by means of multiple routes. The phonological file can be accessed directly from the visual form or through spelling to sound conversion rules. The semantic file can be also be accessed directly from visual form. In addition it can be accessed through morphological decomposition, a process whereby affixes are stripped from the word form and the root is then looked up, or through phonological recoding, a process by which a phonological code is activated and accesses semantic information in the same way as in listening.

Another major difference which further distinguishes the various lexical instance models are the ways in which ambiguity in the activation of the lexicon is resolved. I will briefly describe the differences here, then describe them in detail in the following sections. Logogen models (Morton, 1969; Morton, 1979) rely on two different strategies: the first is a horse race between the logogens being activated - the closest match gains the most activation the fastest and wins. The second is context, and is employed when more than one word is presented. The mechanism by which context operates in logogen models is not specified. However, one can surmise that the contextual system knows the meaning of the word being recognized and uses that information to enhance the activation of the underlying form in a top down fashion. Verification models (Becker, 1976; Herdman and Dobbs, 1989; Kellas, Ferraro and Simpson, 1988) rely upon the checking of word candidates which have been activated by bottom up visual information against an image of the word being processed in sensory buffers; the process of verification, from which they get their name. Interactive activation models (McClelland and Rumelhart, 1981) rely upon a horse race and context like the logogen models do, but they also use lateral inhibition to resolve ambiguity.

Lateral inhibition is a process by which an activated representation in memory represses similar representations which are also being activated at the same level of processing. Finally, lexical search models rely upon constrained access to the lexicon and context for the resolution of ambiguity (Taft and Forster, 1975; Taft, 1985). Constrained access to the lexicon is accomplished in two ways by the lexical search models: The first is morphological decomposition; a process which avoids having to search for the many words starting with frequent prefixes by searching for their more unique roots instead. The second is the use of an access code to the lexicon, consisting of a portion of the orthographic form, which avoids having to search the entire lexicon at once.

Logogen Models

Logogen models employ direct access to the mental lexicon, which consists of a set of individual permanent representations of all known words (Morton, 1969; Morton, 1979). The word units, which represent the physical form of the word (spelling), receive information from all sources. Bottom up information about the form of the word from analysis of visual features and top down information about the meaning of the word from context add to the activation of the units until one of them surpasses its threshold and produces a response. When a response is made, all other information about the word becomes available. In laboratory tasks such as lexical decision or priming, this is the point at which the word is "recognized". When reading, this is the point at which the meaning of the word becomes available. All lexical instance models are centered around this type of lexicon. The flow of information in the logogen models is bottom up, with the exception of the influence of context, which acts in a top down fashion. The logogen model makes no predictions about the attentional demands of recognizing a word but since the analysis of information is strictly parallel, it is reasonable to assume that no specific stage of the logogen model engages attention more than another. A representation of the flow of information in the logogen model is presented in Figure 1.

Insert Figure 1 About Here

If the word to be recognized were "bard," as in Figure 2, visual analysis of the word in the logogen system would result in the activation of "bard" and its neighbors. The neighbors of "bard" are the words which are similar in spelling. In addition to differences in activation from exactness of match, the activation of logogens in the lexicon is further distinguished by the contextual system. In the case of this example, if the context happens to be poets, the "bard" node would get some extra activation from the contextual system.

Insert Figure 2 About Here

The logogen model derives its empirical support from the frequency effect in word recognition; the phenomenon in which high frequency words are responded to faster than low frequency words (Scarborough, Cortese, and

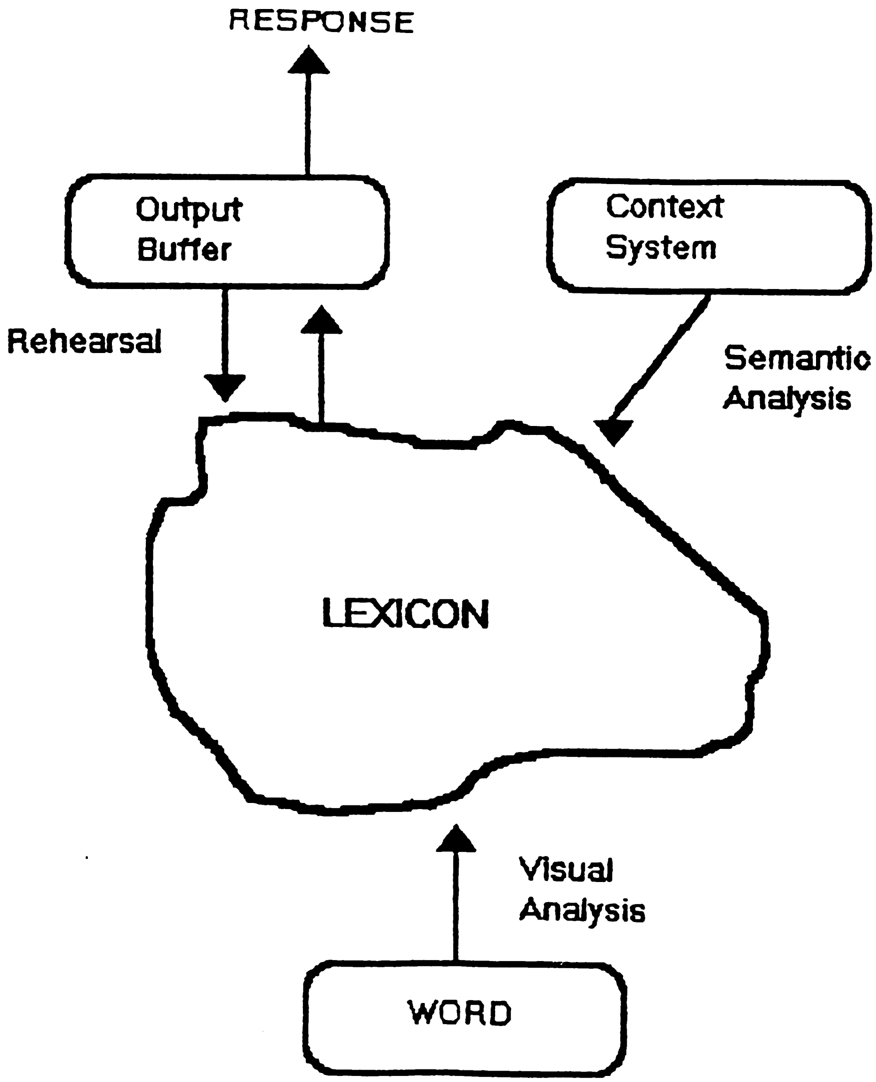


Figure 1: The Logogen Model - Architecture

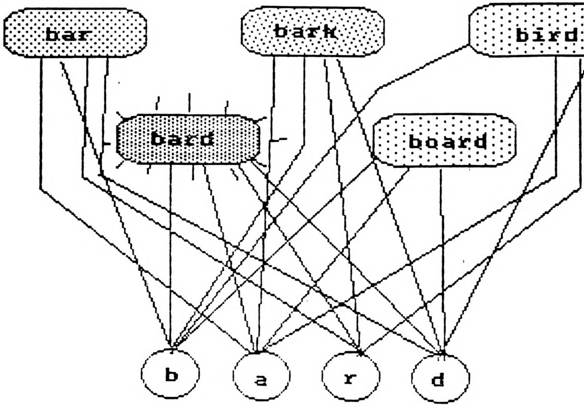


Figure 2: The Logogen Model - Detail

Scarborough, 1977). According to the logogen model, thresholds for high frequency words are lowered, resulting in a decision with less activation.

Morton and Murell (1974) expanded the logogen model to account for facilitation in recognition between words which are acoustically and morphemically similar over words which are just acoustically similar. Their explanation is not very detailed, but it entails the existence of logogens for morphemes as well as words. The value of this addition to the model will become apparent when evidence for the lexical search model is reviewed later in this paper.

Interactive Activation Models

The interactive activation model of McClelland and Rumelhart (1981) is similar to the logogen model in that each word has a permanent representation in memory which is accessed on the basis of orthographic form of the visual stimulus. These permanent representations receive input from both top down and bottom up processes, much as in the original logogen model. The interesting addition in the interactive activation model is the concept of inhibition. Competition at the various levels (word and letter levels) is resolved by an activated representation repressing all other representations. This reduces the possibility that mutually exclusive representations will be confused. Without inhibition in a logogen-like model, two words which are similar in form might both surpass threshold on the basis of perceptual information alone. It is through this competition that ambiguity in the activation of the lexicon is resolved. In the earlier example, when "bard" becomes activated it subtracts activation from its orthographically-defined neighbors "bar", "bart", "bird", etc. (see Figure 3). This reduces the possibility that "bar" will be accidentally recognized. The interactive activation model also uses top down input to the words from context, as the logogen model does (Morton, 1969), to disambiguate words (Rumelhart and McClelland, 1981).

Insert Figure 3 About Here

Activation, inhibition, and contextual information all flow in parallel in the interactive activation models. This model makes no specific predictions regarding attention demands. Therefore, the general flow of information in the interactive activation model does not differ much from that shown for the logogen model in Figure 1.

The process of inhibition also has benefits at the letter level in the interactive activation model. Namely, it allows the model to explain the word superiority effect, the improved perception of letters when seen in the context of words (Reicher, 1969; Cattell, 1886, both cited in McClelland and Rumelhart, 1981). The word context serves to distinguish letters by the addition of top-down activation and the ambiguity between letters which are similar in form is reduced by inhibition.

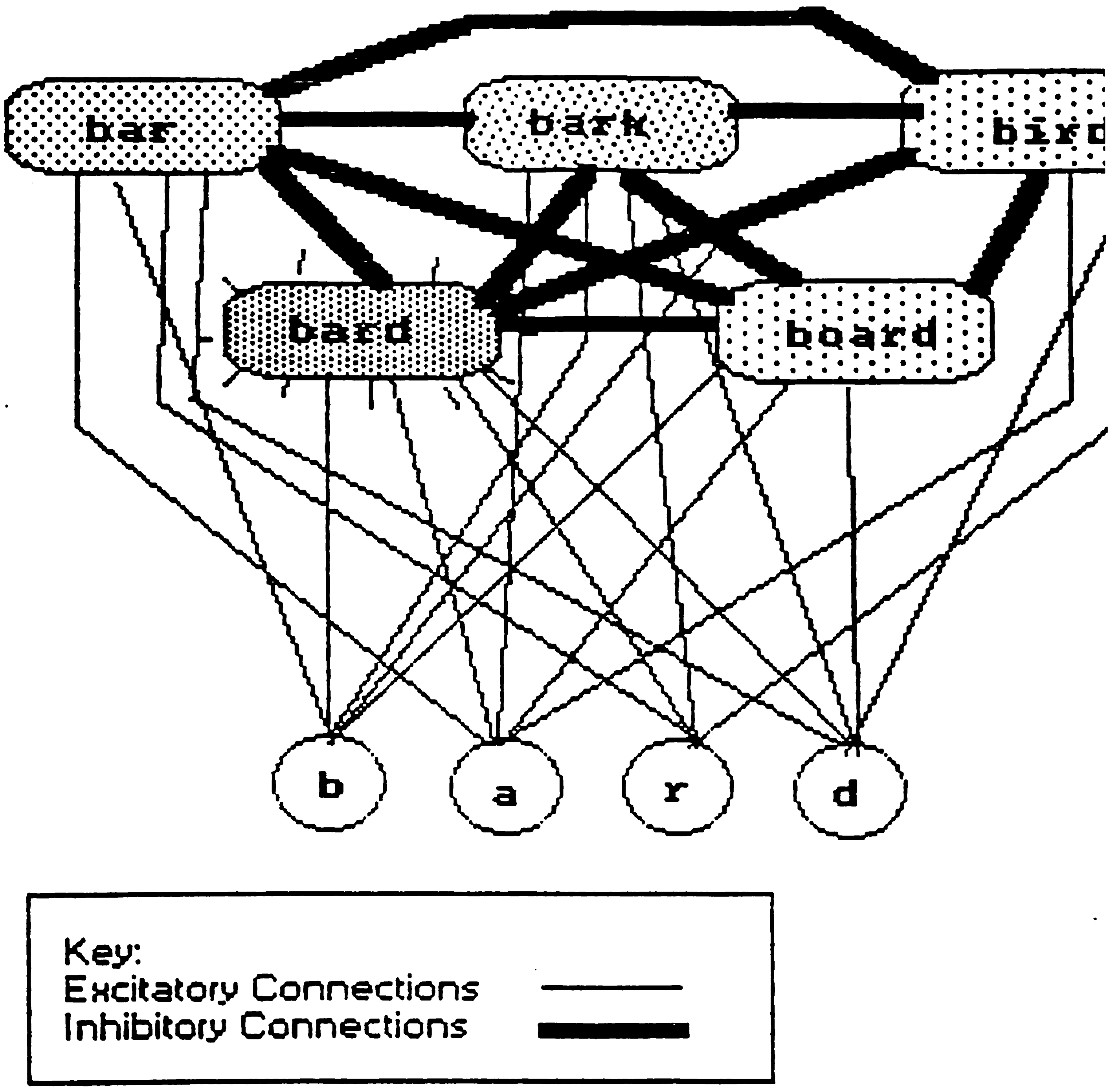


Figure 3: The Interactive Activation Model

Parallel Distributed Processing

The Parallel Distributed Processing model of word recognition and naming (Seidenberg and McClelland, 1989) represents a radically different approach to the storage and access of lexical information in memory. In contrast with logogen models, which employ individual memory representations for each word, the PDP model instantiates a word representation as a pattern of activation across a series of word feature units. The implemented model consists of three layers: input orthographic units, hidden units, and phonological units. The strengths of the connections within these three layers is where memory is located. The model produces a pronunciation from a written form by activating the proper phonological units when a particular pattern of activation is seen on the orthographic input units. That is, when it sees a particular word's pattern on its input side (it reads it) it produces that word's pattern on its output side (it pronounces it).

The model learns which phonological units should be active when a particular set of orthographic units is active through a back-propagation learning rule. Simply stated, when the model pronounces a word, if it makes a mistake, an omniscient teacher changes the strengths of the connections in the hidden units to make it more probable that the model will generate the correct pronunciation the next time.

The ideal version of this model is rich and complex; theoretically there is the possibility of more than one route from orthography to phonology. However, the implemented model is far simpler. In a recent debate on word recognition, Seidenberg (1989) claimed that if there is more than one route to pronunciation, his implemented model represents "rule-governed" or "assembled" orthographic to phonological coding. Much like the Rumelhart and McClelland (1987) past tense verb learning model produced rule governed performance in producing the past tense of English verbs without explicitly representing rules, the PDP model of word pronunciation is intended to produce seemingly rule governed behavior in pronouncing English words without explicitly incorporating orthographic to phonological conversion rules. Besner, Twilley, McCann, and Seergobin (1990) report that the PDP model is accurate at pronouncing words which it has seen before but performs poorly on words which it has not seen. Thus, as an orthographic-to-phonological conversion route, this model is deficient in that it acts like a phonological dyslexic.

Insert Figure 4 About Here

However, the important aspect of this model for the current discussion is the architecture: information flow and the role of attention. The architecture of the implemented model is represented in Figure 4. Information flow within the implemented model is along a single route from orthography, through the hidden units, to phonology. Theoretically, the interaction between these units is bi-directional, however in the implemented model there is no connection returning from the phonological output units to the hidden units. The model makes no explicit predictions as to the use of attention in the processing of words.

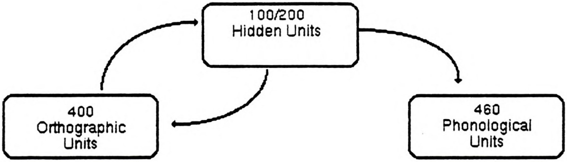


Figure 4: The PDP Model

However, it is consistent with the implemented model that attention could act globally or universally, to speed or inhibit the flow of information in the network as a whole.

Mozer's BLIRNET

Another approach to visual word recognition and one in which the role of attention is explicitly defined, is represented by Mozer's BLIRNET (Mozer, 1987; Mozer and Behrmann, 1990). This model has not been developed to the extent that it explains the entire corpus of data on word pronunciation, but it is important in that it specifies a role for attention in the process of word recognition.

The model consists of three main mechanisms. The visual object recognition system, MORSEL, is a hierarchical network which begins with the recognition of simple features, such as lines, and progressively sums these features over space to form more complex items. The recognition of letters and words is handled by a set of specialized mechanisms which make up a separate part of the model called BLIRNET. Attention in this model serves to enhance the activation of information originating from the region of visual space in which the word recognition system is trying to read. That is, attention controls the flow of information from the environmentally-coded spatially specific representation in MORSEL to the non-spatial representation in BLIRNET. The function of attention is to keep the reading system from biting off more than it can chew. The model predicts that when spatial attention is damaged, neglect of parts of words being read will occur. This is supported by clinical data from patients with spatial neglect caused by brain damage, who also neglect portions of words (Mozer and Behrmann, 1990; Hillis and Caramazza, 1990).

Verification Models

Verification models represent a solution to the competition problem in lexical access without the use of inhibition. According to verification models (Becker, 1976; Herdman and Dobbs, 1989; Kellas, Ferraro and Simpson, 1988), there is activation of words in the lexicon but no inhibition between word or letter units, much as in the initial stages of the logogen model. An incoming word activates all of its candidates in the lexicon in parallel based solely on sensory information. All words from the lexicon which have surpassed their threshold are then submitted to the verification stage, in frequency order. The verification stage uses attention to compare the word representation retrieved from the lexicon with the iconic memory for the word. When the verification model is presented with the quandary in Figure 3, all the words similar to "bard" remain activated and attention sorts out the mess serially by comparing the words which are activated with the initial visual input. This is the critical attention demanding stage referred to as verification. Once a word has been selected by the verifier on the basis of form, other information, such as information about its meaning, become available. No mention is made as to whether this information is contained in a single file or in multiple files but the access to all information is based upon visual form driven access followed by verification.

The flow of information in the verification model, seen in Figure 5, is different from the logogen and interactive activation models in that there is now one process which requires attention, the verification process. All other information in the verification models is processed in parallel and does not engage attention.

Insert Figure 5 About Here

Support for the verification model comes from studies of attentional demands during word recognition (Becker, 1976; Herdman and Dobbs, 1989). Verification models predict that since low frequency words take longer to recognize in a lexical decision task than high frequency words do, there should a longer engagement of attention during the recognition of low frequency words as compared to high frequency words. The measure of attentional demands most commonly used is tone detection latencies. The reasoning behind this is that tone detection requires attention and when attention is engaged elsewhere, such as by the verification process, tone detection latencies will be longer. In lexical decision studies, tone detection latencies are typically longer during the recognition of low frequency words than during the recognition of high frequency words; a difference attributed to the verification process.

Kellas, Ferraro, and Simpson (1988) demonstrated that frequency is not the only factor determining the attention demands of word recognition. The number of meanings which a word has affects the attention demands of word recognition

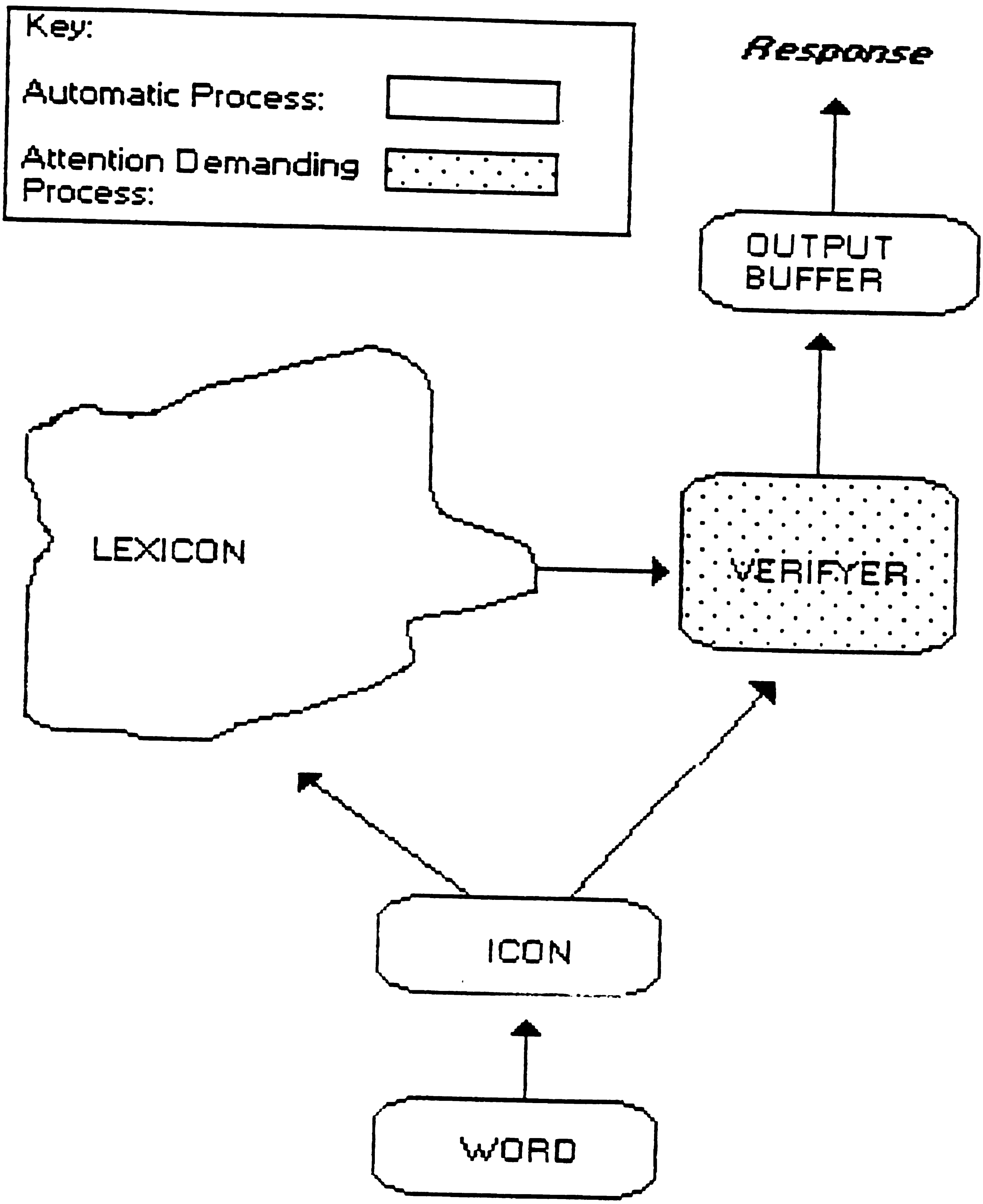


Figure 5: The Verification Model

as well. In Experiment 1 they find that tone detection latencies during lexical decision were fastest for pseudo-words, next longest for single meaning words, and longest for homographs (words with more than one meaning for a single spelling). That is, the attention demand of word recognition increases as the number of meanings of the word being recognized increases. In Experiment 2 they found similar results using a memory load manipulation during lexical decision. Subjects performed a lexical decision task while maintaining a set of digits in memory. The effect of digit load on lexical decision times was inversely related to the number of meanings the stimulus possesses. That is, if you tie up attention with a secondary task which is attention demanding, the recognition of words with multiple meanings suffers most. Presumably this is occurring because resources which the verification process requires for its operation are being engaged elsewhere.

<u>Lexical Search Models</u>

In lexical search models (Forster, 1976; Taft and Forster, 1975, 1976) words are stored in a single lexicon and are accessed on the basis of physical form, but indirectly, through the use of so-called "access codes." In the course of recognizing a word, the visual representation is first subject to morphological decomposition, a process in which the affixes and inflections are stripped from the word, leaving only the root. An access code is then found for the root and it is this code which is used as a cue for searching the lexicon.

The access codes are stored in a file which is separate from the lexicon. Roots are stored as a single entry in the lexicon, no matter how many forms they take in combination with various affixes and inflections. Stored along with the roots is information concerning which affixes and inflections they may take to form a legal word. It is not clear what other information is stored along with the roots in the main lexicon but it is clear that the entry in the main lexicon serves as the sole gateway to all information about a word. If an entry is not found for a root in the lexicon, or if an access code is not found for a root, then the access code is found for the entire word and it is searched for in the lexicon. If there is still no entry found, as in the case of nonword stimuli in the lexical decision task, the conclusion is reached that the stimulus is not a word.

Information flow in the lexical search model is bottom up, with the exception of the feedback loop from the decision mechanism which operates when the decomposition process fails. For example, when an attempt is made to decompose a pseudo-prefixed word, such as "repeat", the stem is not found in the lexicon and the process fails. The lexical search models make no explicit predictions as to the use of attention but such predictions can be deduced from predictions about the time taken to recognize words. Specifically, the time taken for a word to contact its entry in the lexicon will increase when the morphological decomposition is incorrect, resulting in an attempt to access a stem which is not stored in memory. In these cases, the access code for the word must be determined again, which is an added step performed serially, a situation in which attention is likely to be engaged. While there is evidence for decomposition (Taft

and Forster, 1985, 1976; Taft, 1981), there is no proof of the attention demands associated with the use of morphological decomposition. This view of information flow in the lexical search model is depicted in Figure 6.

Insert Figure 6 About Here

The morphological decomposition strategy employed by the lexical search model has the benefit of storage efficiency, in that a single stem is not represented more than once in the lexicon. However, this efficiency is at the cost of processing complexity in that there is a complex set of rules to decompose words. Because storage efficiency in the lexical search model comes at the cost of considerable processing complexity, one might ask for evidence for this occurrence of this extensive processing before accepting this complexity. After all, the idea underlying the logogen, interactive activation, and verification models - one representation per word - is a simple and intuitively quite plausible one. An answer to such a question would be possible with the dual task interference methodology employed in this investigation.

The Activation-Synthesis Model

In many of the models that have been reviewed so far, word pronunciations are stored along with the memory representations for the words. However, people can pronounce words they have never seen before. This raises the question of what mechanism is responsible for the generation of pronunciations of

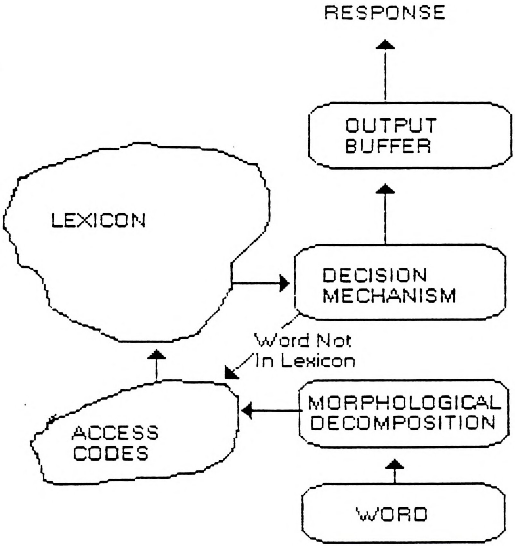


Figure 6: The Lexical Search Model

novel words, such as nonwords. One approach to this problem is that nonwords and new words can be pronounced by analogy to known words. This approach is taken by Glushko's (1979) activation synthesis model. Another approach to this problem is to generate new pronunciations using a set of rules, the approach taken by dual route models of spelling to sound (Coltheart, 1978; Paap and Noel, 1989, 1991; Paap, McDonald, Schvaneveldt and Noel, 1987) which will be discussed next.

Glushko's model operates in two stages: activation and synthesis. Activation is the first stage and it works like the initial stages of the verification models, the reading of a word activates a number of candidates in the lexicon which are similar to it in orthography. When these representations are accessed, information about their pronunciations becomes available. In the second stage, synthesis, the pronunciations of these candidates are used to generate a pronunciation of the new word by analogy.

Glushko supports this model with evidence that naming latencies for pseudowords show consistency effects similar to the words the nonwords were constructed from. The consistency effect in word naming (Baron and Strawson, 1976) is that words which sound similar to their orthographic neighbors are pronounced faster than words which do not sound similar to their orthographic neighbors. Glushko (1976) found that nonwords constructed from consistent words were pronounced faster than nonwords constructed from exception words. This supports the notion that these words are pronounced by analogy to known words and not by pronunciation rules. Rosson (1985) demonstrates that this analogy effect only occurs when the nonwords contain spelling patterns which are not frequent in English. She calls these words weak rule governed words. Rosson concludes from this data that some pronunciations can be generated by rules and some pronunciations are generated by analogy.

The Dual Route Model of Spelling To Sound

Another approach to generating word pronunciations is seen in dual route models of spelling to sound (Coltheart, 1978; Paap and Noel, 1989, 1991; Paap, McDonald, Schvaneveldt and Noel, 1987) and in the Parallel Coding Systems model (Carr and Pollatsek, 1985). In dual route models, as the name suggests, there are two routes from a word's written form to its pronunciation. One route is the lexical route, in which the memory representation of the word is directly accessed from its visual form and the stored pronunciation is retrieved. There is no mention in the dual route models of whether the pronunciations are stored in the same lexicon as the visual form of the word by which they are accessed. The PCS model, which is more elaborate than the dual route models, has the pronunciations in a separate lexicon, but this is a representational issue which is not the primary focus of this paper. The other route to pronunciation in a dual route model is the non-lexical route, and it involves forming a rule generated pronunciation. These rules are called Orthographic to Phonological Conversion rules, hence the non-lexical route to pronunciation is often called the OPC route.

The dual route model of Paap et al. is set up in a horse race fashion. Both routes work independently on the recognition of the word and the route that finishes first wins. In the event of a tie, the direct lexical access route is given precedence but if the two answers conflict, attention is required to sort out the mess. The precedence given to the memory route makes sense when one considers the infrequency of mispronunciations of exception words in the naming literature. [Seidenberg (1985) reports an error rate in naming inconsistent words of less than 1 percent]. Attention is also required in the generation of rule based pronunciations in the OPC route, whereas the direct rule operates more automatically, drawing less upon central attentional capacity. A representation of the flow of information in this model is depicted in Figure 7.

Insert Figure 7 About Here

Support for the model comes from experiments in which Paap and Noel (1991) used attention demands to separate the responses of two routes to pronunciation. By taking advantage of the supposed attentional demands of assembling a rule based pronunciation, they were able to slow down the OPC route by imposing an attentional demand during naming. This eliminated response competition which occurs when the two routes simultaneously deliver conflicting pronunciations, such as with low frequency, exceptionally spelled words. The measure they used is naming latency.

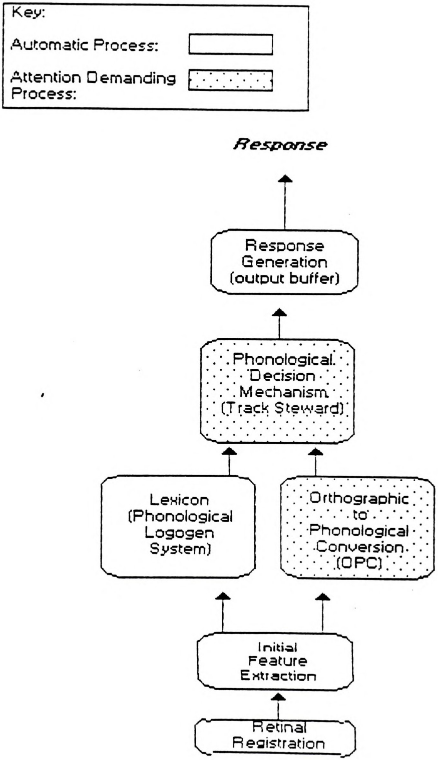


Figure 7: The Dual Route Model

The details of their test are as follows. Two key differences in the time course of naming latency are (1) high frequency words are named faster than low frequency words (Rubenstein et al., 1970). (2) Words with exceptional spelling-to-sound translation patterns (inconsistently pronounced words) are pronounced more slowly than words with regular rather than exceptional spelling-to-sound patterns (consistently pronounced words), but only when both are of low frequency (Seidenberg, et al., 1984; Taraban and McClelland, 1987). A word with an inconsistent pronunciation is not pronounced in the same way as its neighbors; as in the case of PINT which is pronounced differently than its neighbors LINT, MINT, and HINT. A word with a pronunciation consistent with its neighbors is one like FROG which is pronounced just like its neighbors BOG, FOG, and LOG.

According to the dual route model, when a word is low in frequency, the lexical access route, which is on average faster than the OPC route, is slow enough that it retrieves the stored pronunciation at the same time that the OPC route delivers the assembled pronunciation. The two pronunciations conflict and it is the resolution of this conflict that takes the time which causes the difference in naming latency for consistent and inconsistent words of similar low frequency. Paap and Noel (1991) found that this difference is significantly reduced under a heavy memory load. Whereas the memory load interfered with performance on high and low frequency regular words as well as high frequency exception words, with greatest harm done to the low frequency regular words, memory load actually improved performance on low frequency exception words. (see Figure 8). This result is quite striking. They interpreted this result as a release from the conflict between the two routes to naming.

Insert Figure 8 About Here

This dual task interference procedure used a modified version of a memory load task developed by Sternberg (1966) in which one or five digits were presented visually and a single digit probe was visually administered three seconds later. Maintaining the single digit in memory represented a low attentional demand and maintaining five digits in memory represented a high attentional demand. The naming task was presented during the retention interval at a delay of one to two seconds after the offset of the presentation of the memory set. The purpose of the random delay was to avoid subjects anticipating the naming task and switching attention in advance.

Under the five digit load Paap and Noel found that naming latencies for inconsistent words were faster than under the one digit load. The reason for this is demonstrated in experiment 2, where they showed that the OPC route engages attention and lexical access does not. To show this, they used a dual task paradigm that required tone detection during naming. Tone detection also engages attention and since attention is often regarded as a limited resource (although some theorists believe that the limitations lie elsewhere), when the primary task (pronunciation) requires attention, tone detection latencies will increase. Tones were presented over headphones (otherwise the tone would set

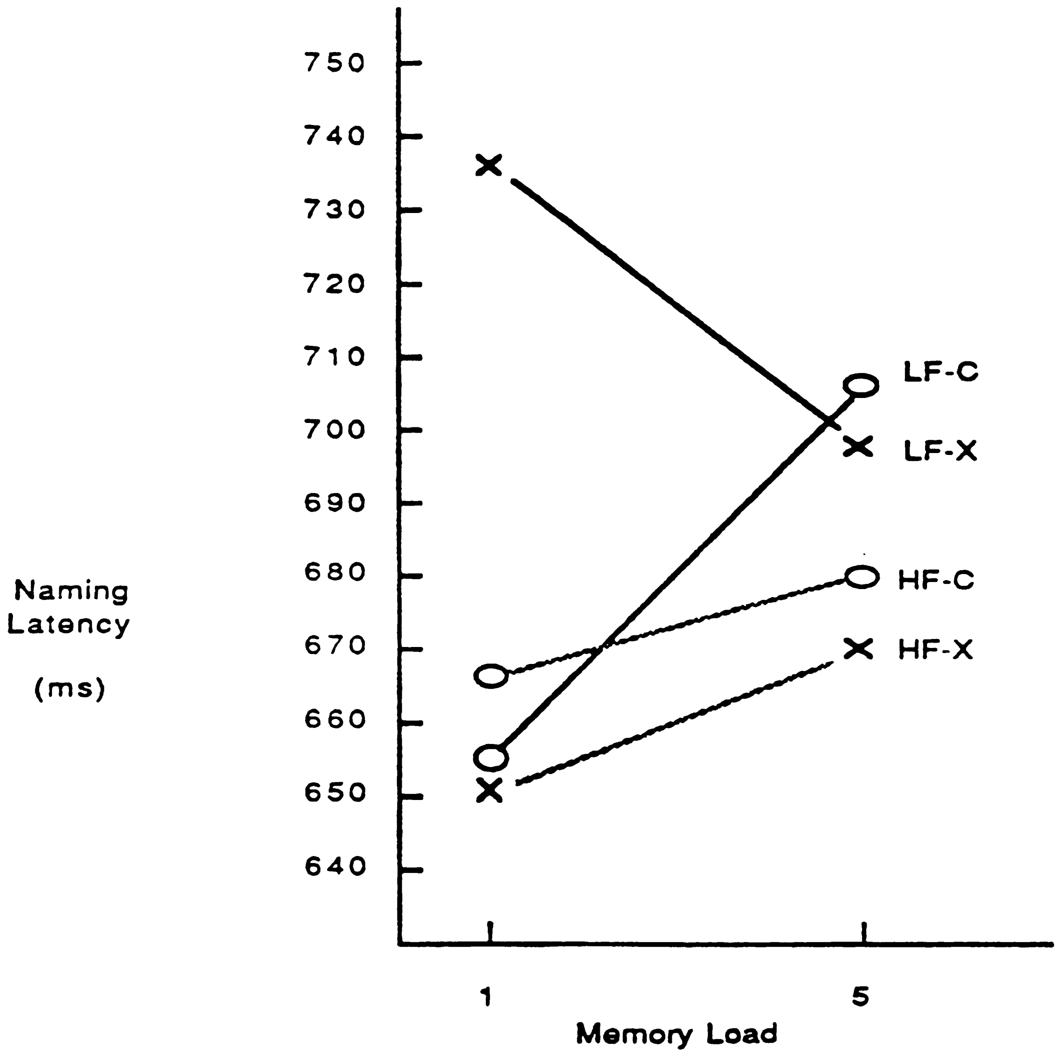


Figure 8. Naming time as a function of memory load for the four types of words: high-frequency exception (HF-X), high-frequency control (HF-C), low-frequency exception (LF-X), and low frequency control (LF-C). (Taken from Paap & Noel, 1991).

off the voice key). There were two groups of subjects: one group was presented with all exception words and the other with half exception words and half consistent words. The prediction that dual route model makes is that the use of the OPC route can be controlled by the subject (e.g. Carr, Davidson, and Hawkins, 1978), and subjects presented with all exception words will shut down the OPC route and use direct access only. Since direct access is not attention demanding and the OPC route is, the dual route model predicts that auditory probe detection latencies will be shorter for the all exception group because they are using direct access and attention is therefore unoccupied. Paap and Noel did find faster probe latencies for the all exception group as compared with the group presented with only half exception words. This lead them to conclude that (1) the use of the OPC route is under the subjects control and (2) attention is engaged by the OPC route.

Given the results from their second experiment, the conclusion Paap and Noel reached from their first experiment was that the memory load, which is attention demanding, slows the OPC route, thus eliminating the competition between routes at response time when a single pronunciation must be produced. Paap and Noel note four key assumptions, upon which their results rely:

1) There are two functionally independent pathways for accessing phonological codes.

2) Assembling phonological codes takes more attention than looking them up in the lexicon.

3) The slower naming latency to exception words is caused by competition between two conflicting phonological codes at response time: the rule generated code (which is probably misleading) and the lexically accessed code.

4) The benefit of the memory load, which is the reduction of competition at response time, is greater than the cost of performing the two tasks simultaneously.

There is, however, a fifth untested assumption which is key to the explanation offered by Paap and Noel of this effect. A digit span task was used for the memory load. A digit span task is indeed highly resource demanding but short term memory is partly articulatory in nature (Baddeley and Hitch, 1974). Concurrently performed articulatory tasks interfere with each other (Brooks, 1968); this interference between two tasks which are articulatory in nature is potentially quite different from competition for central processing resources, that is, attentional interference. Structural interference is described by Neumann (1987) as the simultaneous use by numerous tasks of the same encoding, decision, or response mechanism.

If subjects were to remember the digits by repeating them silently, the apparent shutdown of the OPC route under load could either be due to the attention shortage imposed by the task as Paap and Noel suggest or due to cross-talk between phonological/articulatory information active in short term memory and the phonological units in the OPC route. Thus, the effect could be due to structural interference and not due to the central processing demands of the OPC route. The level of this interference might be the phonological/articulatory representations within the OPC route, which would be activated both by the digit memory representations and the word being pronounced.

For this structural interference account to explain the results of the first Paap & Noel (1991) experiment would require that the operation of the OPC route suffer more from cross-talk interference than the direct access route. That is, in the case that a low frequency exception word is being pronounced, the OPC route, which usually causes interference with an incorrect pronunciation, would be slowed by cross-talk while memory remained relatively unaffected. If this were not the case, the pronunciation of low-frequency exception words would not speed up under load. One place where the cross-talk might occur, causing such an effect is among phonological/articulatory units which make up the representations being manipulated in the OPC route. The maintenance of a digit memory load could be causing competition among these units, which could in turn slow processing through the OPC route. A consideration which arose late in the time course of this investigation was that the cross-talk might also be occurring at a higher level, with the word representations of the digits interfering with the operation of the OPC route. That is, if word representations play a role in the generation of pronunciations, as in the activation-synthesis model, interference at this level might have caused the Paap and Noel results.

This raises a puzzle in regard to the architecture of the dual route model. For phonological/articulatory representations to be effected within the operation of the OPC route but not the memory route requires some dissociation of these units in the two routes. That is, if the OPC route is effected by cross-talk and the memory route is not, there has to be some place at which they diverge. Or if it is the word representations interfering with the operation of the OPC route, higher level word representations must act on the OPC route in a manner different than they act on direct access to the lexicon.

Paap and Noel acknowledge this uncertainty as to the locus of the interference effect, and while the cross-talk alternative does not necessarily rule out the dual route model, it does call into doubt the functional architecture of the OPC route as Paap and Noel see it. This means that the surprising results of their first experiment could be due to interference between the phonological/articulatory units, or due to cross talk with word representations in working memory, instead of being due to the attention demand handicapping the OPC rules.

A resolution of the question concerning the role of interference with the OPC route is important to both the dual route model and the PCS model. This question can be answered by varying the type of interference which is generated by the memory task. The idea is to use interference tasks which cause attentional, lexical, or articulatory interference separately. Thus, the effect of different kinds of crosstalk on word pronunciation can be assessed separately from the effect of attention demand.

If the Paap and Noel results are due to crosstalk between the articulation of the digits and the representation of the word being pronounced, their pattern of results should appear with a task which causes articulatory interference but not with a task which causes only attention demand. If their effect is due to cross talk

with lexical representations, it should appear with a task which causes lexical interference. If their effect is due only to attention demand and not crosstalk, their effect should appear with a memory task which causes attention demand. Because the crosstalk tasks probably also cause attention demand, the effect may show up in these tasks as well, but then the amount of attention demand will have a direct relationship on the size of the effect. If their result is due to the combined effect of attention demand and crosstalk, their pattern should appear only in tasks which represents both high attention demand and crosstalk.

Consequently, three types of memory stimuli were initially chosen for use in the naming experiment to assess where the interference with the OPC route was occurring. (1) Memory for digits, an exact replication of the Paap and Noel experiment. (2) Memory for nonsense syllables, a task intended to represent a relatively heavy articulatory demand that ought to engage the same phonological/articulatory representation as the OPC route. (3) Memory for pictures, a condition which was intended to be a manipulation of attention demand relatively free of articulatory demands. The pictures used were random geometric shapes. The random shapes were chosen because they should not have names associated with them, since they had never been seen by the subjects before the experiment. These nameless shapes were chosen so that articulation would be minimally involved in memory for these items. If subjects do occasionally remember the shapes by naming them, at least the articulations associated with the shapes will not be as consistent or strong as with the articulatable stimuli such as digits and nonsense syllables, and they certainly will not be derived by the OPC process. A fourth condition, memory for high frequency nouns was added later when it became apparent based upon preliminary data analysis that interference with lexical memory representations might be necessary to achieve a speedup in the naming of low frequency exception words. The implications of this possibility will be explored later.

The key assumptions these interference predictions are based upon are the following:

1) Remembering digits, nonsense syllables, and random shapes can be made equally attention demanding by adjustment of list length, and therefore all three conditions will produce attention loads.

2) The OPC system may be constructed in such a way that the repetition of a constrained set of codes leaves the rest of the system available to process other words.

That is, maintenance of the memory set interferes with phonologically mediated access to word representations while leaving direct access to word representations relatively unaffected. Alternatively, repetition of a constrained set of codes may cause interference in the OPC system, which would in turn influence the relative speed of the OPC and direct lexical access routes to word memory.

The calibration experiments were intended to assess whether the attention demands of the load tasks were equivalent and to adjust the tasks to achieve equivalence in the event that they were not.

Chapter II
Calibration Experiments

Two experiments were performed to investigate the attentional demands of the three tasks. In these calibration experiments three load tasks were combined with an auditory attentional probe task to determine attentional demands. Auditory tone detection performed at various delays following the offset of the study set in the Sternberg task, a procedure similar to Paap and Noel's experiment 1, gave an indication of the availability of attention. Auditory tone detection was chosen as a measure of attention because it has often been used in the word recognition literature as a measure of available attention (Becker, 1976; Herdman and Dobbs, 1989; Kellas, Ferraro, and Simpson, 1988); and in particular it was the measure used in Paap and Noel's Experiment 2 (1991).

Some theorists maintain that dual-task interference studies, such as tone detection during memory, do not give a measure of available attention but measure only structural interference (Navon, 1984; Neumann, 1987). The point of objections such as Navon's is that the notion of limited resources need not be invoked to explain the outcome of a dual-task interference experiment. It is not the point of the calibration experiments to address the validity of limited resource views of cognition; nevertheless, these criticisms of attention theories are important. Objections such as Navon's are over the explanation of dual-task interference, not the existence of dual-task interference. Regardless of whether the limitation that causes the memory task to interfere with word pronunciation is attentional or structural, assessing and equating the interference generated by each of the memory tasks remains necessary. In the interest of clarity, the interference generated by tasks will be referred to as attention demand, although it is acknowledged that the attentional explanation of interference is disputed.

The goal of the experiments was to assess and try to equate the attentional demands of remembering different types of materials if necessary, by adding or subtracting items from the high memory load conditions in the Sternberg memory task. For instance, if the attention demand of remembering 5 digits were to be lighter than the attention demand of remembering 5 shapes, then the digit condition could be changed to include 6 digits in order to equal the attention demand of remembering 4 or 5 geometric shapes.

Another purpose of the calibration experiments was to assure that all three tasks were attention demanding. To that end, a significant slowdown in tone detection latency with increasing load was expected. While these three tasks have not been compared on the amount of interference they generate in a dual-task paradigm, the slopes of their memory search functions have been compared. The search functions of all three tasks indicate serial exhaustive search (Cavanaugh, 1972), as Sternberg found for digits (1966). However, the slopes of the search functions for the three tasks differ. The processing rate of nonsense syllables is slowest, geometrical shapes faster, and fastest for digits. The relationship between memory scanning rate (processing rate) and attention demand of maintaining the memory load is unknown, but the fact remains that differences among the tasks do exist.

Attention demand was assessed at four memory load conditions in the two calibration experiments. In calibration experiment 1, the memory loads were: 1 item, 4 items, 5 items, and 6 items. In calibration experiment 2, memory loads were 1 item, 3 items, 4 items, and 5 items. Other differences between the two calibration experiments will be explained later. An increase in tone detection latency with increasing memory load will be an indication of increased attention demand. Differences in tone latencies across tasks at equivalent memory loads will be taken as evidence for differing attention demand among the tasks. If necessary, tasks will be equated by varying the number of items in the memory set to minimize the differences in tone latencies between tasks in the high load conditions. It was expected that differences in tone latencies at the low load conditions among the tasks would be non-significant.

Calibration Experiment 1

The purpose of this pilot study was to assess and equate attention demands in the Sternberg task among the three conditions: (1) memory for digits, (2) memory for nonsense syllables, and (3) memory for random shapes.

Method

Subjects

Thirty-two undergraduate psychology students were recruited from the subject pool at Michigan State University. They participated for partial fulfillment of course requirements. Twelve of the subjects participated in each of the digit and picture conditions while eight subjects participated in the CVC condition.

Apparatus

All stimuli were presented and all responses recorded on an Apple Macintosh 512 KE computer (with memory extended to 1 megabyte) under the control of the PsychLab program, version 0.85 developed by Teren Gum and Daniel Bub (1988) at McGill University. Stimuli were presented on the CRT of the Macintosh in black on a white background. Subjects responses were made on the keyboard of the Macintosh. Response keys were labeled in black ink on white adhesive tabs as follows: The "Zz" key was labelled "Tone" for the tone detection task, and for the memory task the "/?" key was labelled "Yes" and the ".>"key was labelled no.

Materials

There were three different types of materials for the memory load task. A different group of subjects received each of the three types of materials because switching between load tasks within subjects might have caused attention demands above and beyond the demand of remembering the material. Descriptions of each type of material are as follows:

(1) The digit load task was a replication of the Paap and Noel experiment. This served as a baseline for comparisons involving the other two conditions. Stimuli for the digit load task consisted of one, four, five, and six randomly selected digits from the set "1,2,3,4,5,6,8,9.The digits 0 and 7 were excluded because their names have two syllables. Paap and Noel also excluded the digits 0 and 7. In the event that the interference is articulatory in nature, the inclusion of

the two digits with two-syllable names along with the one-syllable name digits would cause an uneven load within the set sizes. The four and six item load conditions were not present in the Paap and Noel experiments but were included for the purposes of equating the three different memory tasks.

(2) The nonsense syllable task used consonant-vowel-consonant trigrams (CVC's) as memory stimuli. One unpublished study cited by Cavanaugh (1972) used CVC's as memory stimuli in the Sternberg task. While both digits and nonsense syllables generate articulatory interference, digits have well established memory representations and CVC's do not. Therefore, this task will serve as a relatively pure articulatory interference condition in the naming experiment.

Design of the nonsense syllable task was identical to the digit task with the substitution of a set of CVC's for the digits. A set of 20 nonsense syllables were selected from the Underwood and Schulz (1960) norms, in which they received low ratings of meaningfulness. These 20 nonsense syllables were combined into randomly drawn sets of 1, 4, 5, and 6 items for the memory task. A complete listing of the nonsense syllables used appears in Appendix A.

(3) In the picture load task subjects remembered a set of random geometric forms. Stimuli for the random picture load task consisted of a set of 20 different eight-sided random figures, constructed according to the principles set forth by Attneave and Arnoult (1956), method 2. An example of these drawings appears in Figure 9 and a full listing appears in Appendix B.

Insert Figure 9 about here

These figures were chosen because they should have no consistent name associated with them, since they were both novel to the subjects and abstract in form. That is, subjects have not seen the figures before and they should not look like anything familiar and nameable. Even in the case that subjects name the figures, it is unlikely that all will be nameable and that names will be consistent across subjects. Therefore, while memory for these figures may involve articulation, there is not a consistent articulatory component. Briggs and Blaha (1969) have used Attneave figures in a Sternberg memory task; they find that subjects use a serial exhaustive search; therefore it is predicted that increasing memory load with these shapes should cause a slowdown in tone latencies. Subjects were instructed that naming of the shapes would be detrimental to their memory performance. This was done to avoid naming strategies which pilot subjects not reported here admitted to having used. Following the experiment, subjects were asked whether or not they followed these instructions. Results of this debriefing will be reported later.

Design of this task was again identical to the digit task with the substitution of the figures for the digits. The set of 20 figures that was used was selected from a set of 40 figures by 7 raters. The raters were given a page with all 40 figures and asked to select 20 of the 40 figures which were the most unique, that is, the least likely to be confused with one another. The selections of the raters were

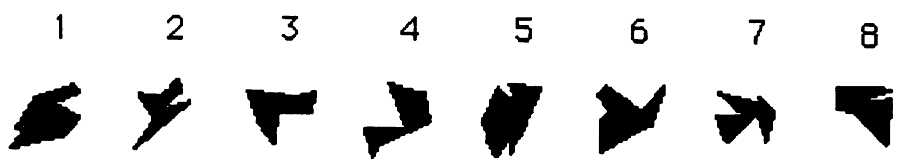


Figure 9: Attneave Figures

averaged, and those figures which were chosen as unique by the most raters were selected for use in the calibration experiments. Randomly drawn sets of 1, 4, 5, and 6 pictures from the final set of 20 were pasted together into images using the Super Paint program, version 1.0 ((c) Silicon Beach Software, 1986). Each of the Attneave figures were 10 x 10 cm. in size. These images were centered on the screen, in black on a white background, spaced approximately 5 cm apart.

Procedure

The procedure was similar to the one used by Paap and Noel (1989; Paap and Ogden, 1982) except that tone detection latency was used in place of naming latency. Subjects were instructed that the primary task was the memory task and that tone detection would occur between the offset of the study set and the test cue. Subjects were instructed to press a button whenever a tone was heard. A copy of the instructions given to subjects appears in Appendix C.

A trial began with the visual presentation of 1, 4, 5, or 6 randomly selected items for the memory load task. All items were presented simultaneously. The duration of the presentation of the study set was determined by the number of items present: 200 ms. per item in the digit condition. Study times for the picture, noun, and CVC conditions were 400 ms. per item, twice that in the digit condition, because in pilot experiments not reported in this paper it was determined that the longer times were necessary for subjects to achieve a sufficient level of accuracy on the memory task.

Following a delay of three seconds from the offset of the study set the probe item appeared and subjects would push the button for "yes" if the item had been presented, or the button for "no" if the item had not been presented. A tone was presented during the retention interval, at a delay which varied randomly between one and two seconds. Frequency of the tone on the PsychLab display was set to 523, a note of "c". Amplitude of the tone was set for 100 (presumably decibels, but it should be noted that the physical units which the frequency and amplitude were represented in on the PsychLab display were unspecified.). Duration of the tone was 50 ms. The randomness of the delay was intended to eliminate any planned switching of attention to the tone detection task.

Subjects first completed 16 practice trials which consisted of two trials each of present and absent targets at each of the four memory loads. Subjects then waited as 80 experimental trials were loaded and randomized by the PsychLab program, this took about two minutes. The 80 experimental trials consisted of 10 trials at each of the 4 load conditions with targets absent and present. Trials were presented in a different random order for each subject. The entire experiment session lasted approximately 30 minutes.

Results

Accuracy Analysis

Accuracy data from calibration experiment 1 were analyzed to explore the relationship between load and percent correct on the memory task. Percent correct responses on the memory task in calibration experiment 1 appear in Table 1 and are plotted as a function of memory load in Figure 10.

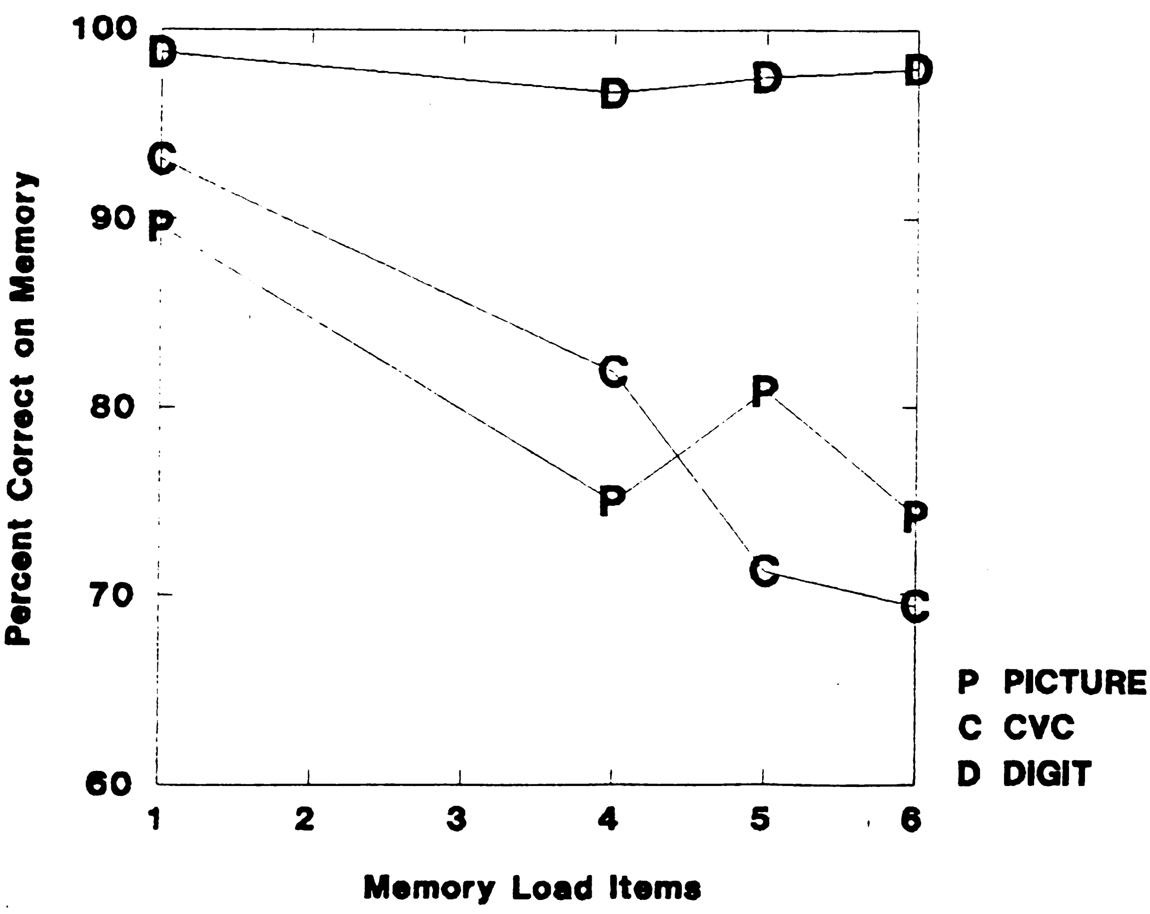
	Memory Load			
Task	1	4	5	6
Digit	99	96	98	98
CVC	93	82	71	69
Picture	90	75	81	74

Table 1: Calibration Experiment 1 - Accuracy on Memory (Percent Correct)

Insert Figure 10 about here

Accuracy levels were subjected to an analysis of variance with the 3 tasks as a between subjects factor and the 4 different load conditions as a within subjects factor. There is a significant decline in percent correct with increasing load evident in the significant main effect of load [$F(3,87)=13.653, p < 0.0001$, $MSE=76$]. There is also a significant difference between tasks in percent correct evident in the significant main effect of task [$F(2,29) = 40.315, p < 0.0001$, $MSE=124$]. There is also a significant interaction between load and task [$F(6,87) =4.616, p < 0.001, MSE=76$]. This can be seen in Figure 10 where percent correct for the CVC and Picture tasks declines across load much more rapidly than percent correct in the digit task.

Calib. Exp. #1 - Accuracy on Memory



Tone Latency Analysis

Tone detection latencies for trials where response to the memory probe was correct were averaged in each of the three conditions in the calibration experiment. These average tone latencies are presented in Figure 11 and Table 2.

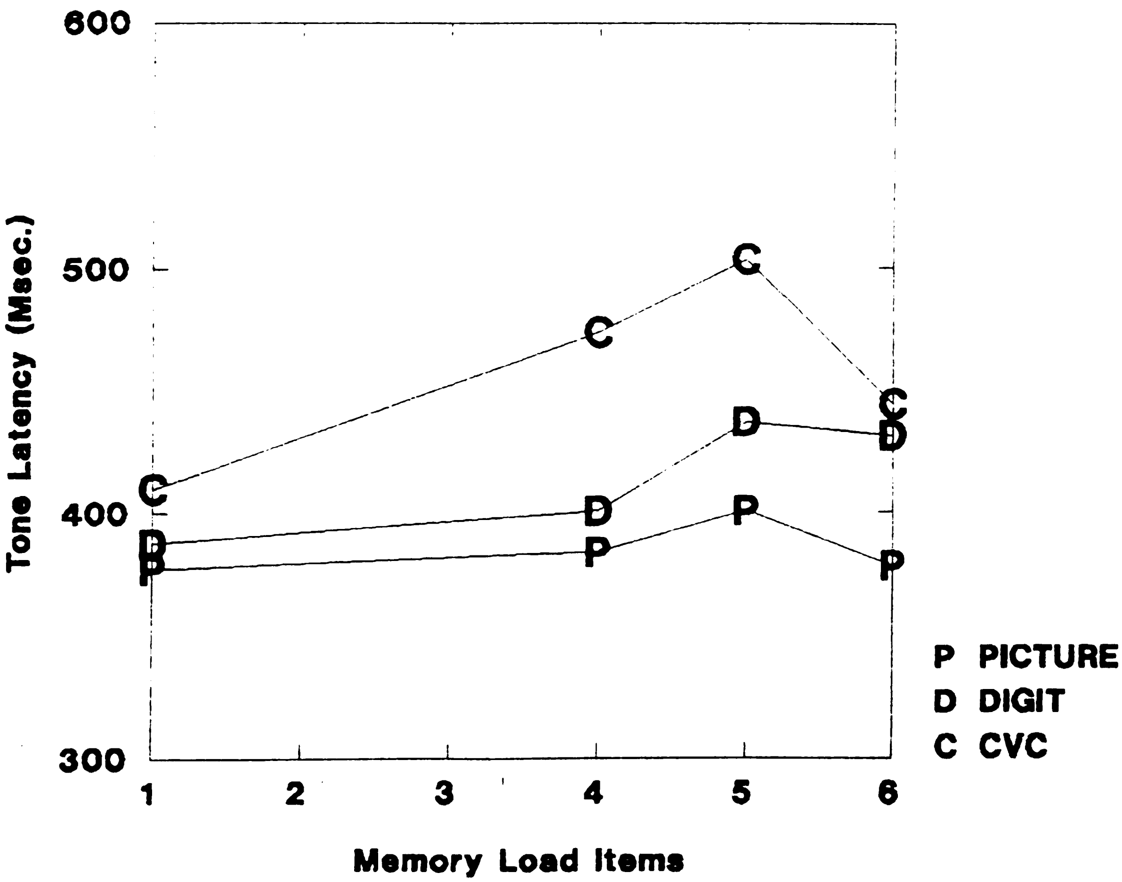
	Memory Load			
Task	1	4	5	6
Digit	388	401	437	431
CVC	410	474	503	444
Picture	377	384	401	378

Table 2: Calibration Experiment I
Tone Latencies (ms.)

Insert Figure 11 about here

In order to determine if the effect of load on tone detection latency was comparable across the three tasks, a repeated measures analysis of variance was performed on average tone latencies with the 3 tasks as a between subjects factor and the 4 different levels of memory load as a within subjects factor. There was no significant difference in the overall size of the load effect across tasks in that the main effect of task was not significant [$F(2,29) = 1.208, p > 0.05$, MSE=43961]. Tone detection latencies did significantly increase as load increased in that there was a significant main effect of load [$F(3,87) = 4.595, p < 0.01$, MSE=3650]. The interaction between load and task was not significant

Calibration Experiment I



[$F(6,87) = 1.020, p > 0.05, MSE=3650$], indicating that load caused a comparable increase in tone latencies in the three tasks.

Although the interaction of load and task was not significant, indicating that the effect of load was comparable across tasks, an alarming feature of the data justified further investigation of this interaction. Specifically, there is a slight speedup in tone latency evident in the CVC and picture tasks when load increases from 5 to 6 items. This speedup is not apparent in the digit task, but there appears to be no slowdown in tone latencies where a slowdown was predicted. A Tukey test fails to reveal any differences among the intermediate load conditions; the critical difference at the 0.05 level of significance was 77.78 ms. A t-test does reveal a significant slowdown in the CVC task between the 5 and 6 item load conditions [$t(11) = 3.563, p < 0.01$]. The t-test also reveals that there is not a significant slowdown between the 5 and 6 item load conditions in the digit and picture conditions. A t-test was used in this situation even though the probability of type-I error is rather high because the purpose of the calibration experiments was to detect any differences among the tasks and correct them. The consequences of a type-II error, missing a difference which is present, would be more serious than a type-I error because tasks which the calibration experiment indicated were equal might in actuality differ.

Trials With Memory Load Errors

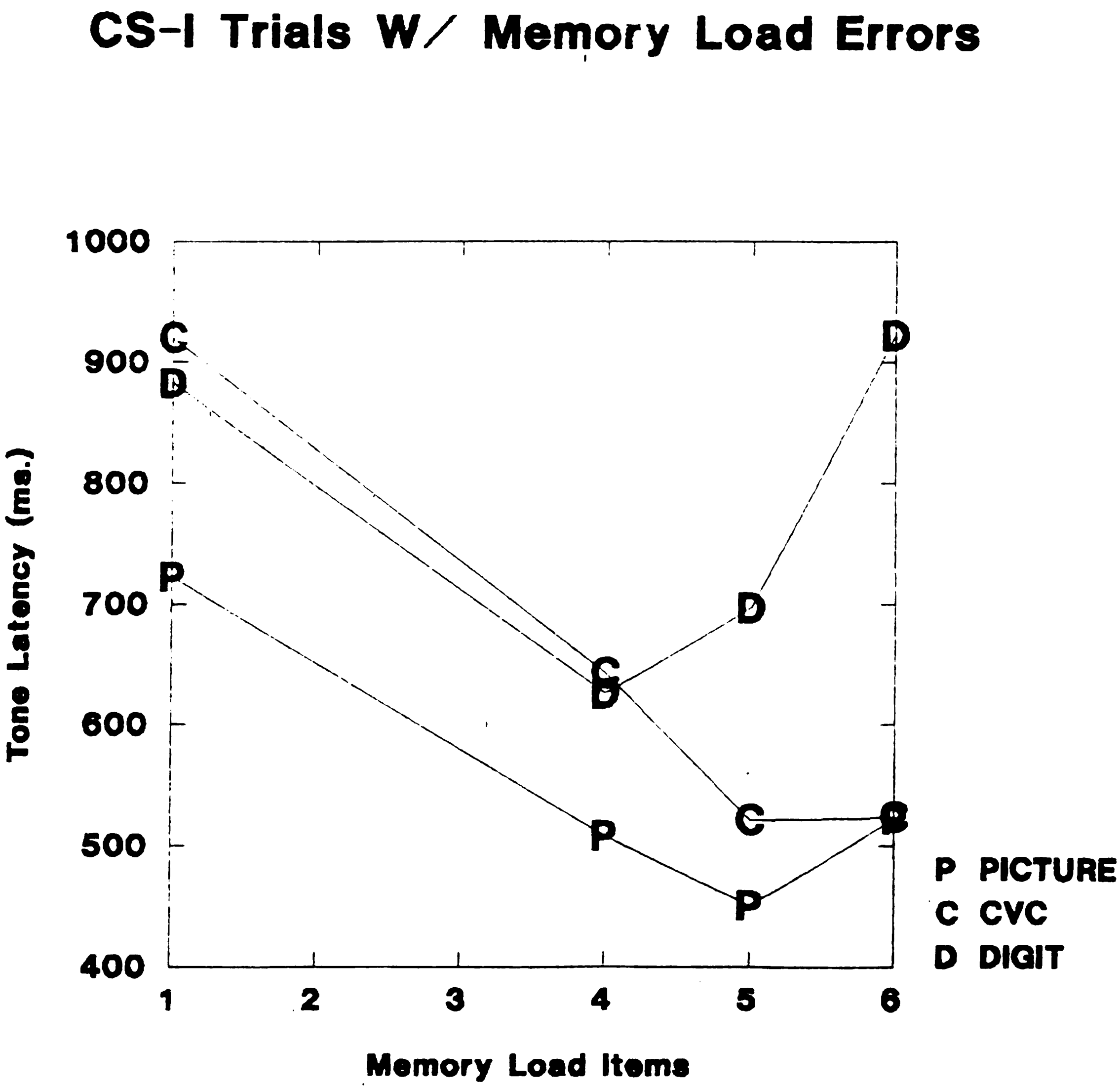
In order to further justify the discarding of trials in which there is an error in the subjects' responses to the memory load were incorrect, tone latencies were determined for those trials. It should be noted that the number of observations within each condition is small, and furthermore that there were not observations in all cells of the design for all subjects. This makes inferential analysis of these results impractical. Despite these problems, this aspect of the data remains interesting, as the question of interest was what happens to tone latency when subjects fail to protect their memory loads? That is, was there a tradeoff between performance on memory and performance on tone latency? Tone latencies for trials in which there were memory errors are plotted for each task in Figure 12.

Insert Figure 12 about here

The important aspect of this graph is that tone latencies decline across increasing memory load, where in the trials in which memory loads were protected, depicted in Figure 11, tone latencies increased with increasing memory load. This is evidence for a tradeoff between tasks. However, tone latencies in Figure 12 are also noticeably higher across the board then on trials for which memory responses were correct.

Discussion

In the calibration experiment, tone detection was used as a probe task to measure available attention. The logic behind this experiment was that when attention was taken up to maintain items in memory, tone detection latency would increase, because tone detection also requires attention. There were two


CS-I Trials W/ Memory Load Errors
1000
900
800
700
600
500
400
Tone Latency (ms.)
1
2
3
4
5
6
Memory Load Items
P PICTURE
C CVC
D DIGIT

predictions of interest: The first prediction was that remembering 4, 5, and 6 items would result in longer auditory probe detection latencies than remembering 1 item. Evidence for this in the ANOVA would be a significant main effect of load, indicating an increasing attention demand with load. The second prediction was that the attention demands of the three tasks might differ. This would appear in the ANOVA as a significant main effect of task and a significant task by load interaction. The tasks then would be equated by choosing load conditions which would in a subsequent ANOVA eliminate the main effect of task and the interaction of task and load.

The first prediction was confirmed. All 3 tasks exhibit an increase in tone detection latency with increasing memory load, indicating an increase in attention demand with load. With regard to the second prediction, there are no apparent differences between the tasks in their overall attention demand, as seen in the lack of a main effect of task on tone detection latency and the lack of an interaction between task and load. However, there are some differences in the tone latencies apparent in Figure 11, which may not have reached significance due to the small number of subjects used in the calibration experiments. Even if the tone latencies are relatively equivalent, there were significant differences in accuracy among the three tasks. Accuracy on the digit task remained high across load while accuracy on the picture and CVC tasks declined significantly across load.

These differences are important for two reasons. First, trials in which there are errors on the memory load tasks will be discarded from the analysis of naming latency data in the naming experiment. These trials will be discarded because it is unclear what is happening when there is a memory error. Comparison of Figures 11 and 12 indicate that something different happens to tone latencies when there is an error in memory performance as compared to when memory performance is accurate. Two differences are important (1) subjects are slower on tone latency when they make memory errors and (2) tone latencies decrease across load in trials with a memory error while they increase across load in trials without a memory error. This suggests that the intended attention demand manipulation, of low load with single item loads and high load with multiple item loads, is not working in these trials. This also suggests that there may have been a tradeoff between the two tasks. However, since latencies overall were slower when there were errors, this does not support the notion that subjects were abandoning their memory loads and leaving attention free for the secondary task.

The second reason accuracy differences among the three tasks are important is that if accuracy in the high load conditions is too low, there will be a smaller number of observations in those cells of the design which use high memory loads, which in turn will lessen the chances that attention demand effects on naming latencies will be detected. Furthermore, even in the 1 item condition accuracy in the CVC and picture tasks is lower than in the digit task.

Yet another reason that the accuracy data are troublesome is that although there does not seem to be a tradeoff between memory performance and tone latency when looking at tone latencies when there are memory errors, there is some evidence for a tradeoff in valid trials between the 5 and 6 item loads. Specifically, in Figure 11 there is a decrease in tone detection latency between the 5 and 6 item memory loads. This difference proves to be significant in the CVC task with a t-test but not with the more conservative Tukey test. The decrease in accuracy coupled with the decrease in tone latency suggests that the subjects are failing to maintain the stimuli in memory in the high load conditions and simply devoting their resources to the tone detection task.

The simplest conclusion which can be reached based upon the data from this experiment is that the CVC and picture tasks are more difficult than the digit task. Consequently, new versions of the task were tested in the second calibration experiment with the following changes: First, rather than drawing the targets from a set of 20 possible items, they were drawn from a set of 8 possible items. Second, instead of using memory sets of 1, 4, 5, and 6 items, memory sets of 1, 3, 4, and 5 items were used. This should serve to make the memory task easier for the subject, increasing percent correct and eliminating the shift of attention to the tone task in the high load condition. The concern here was that perhaps the tradeoff would show up in whatever load happens to be the highest. If this is the case in the second calibration experiment, there should be a speedup in tone latency from the 4 to the 5 item load.

The change in the size of the possible target set also makes the CVC and picture tasks closer analogs to the digit task, as now in all 3 tasks the targets are drawn from a possible set of 8 items. The digit task was not re-done in the second calibration experiment as the addition of a moderate load condition (3 items) was not of interest, just the high and low load conditions which were already tested.

Calibration Experiment 2

Method

Subjects

Sixteen undergraduate psychology students were recruited from the subject pool at Michigan State University. They participated for partial fulfillment of course requirements. Twelve of the subjects participated in the CVC condition while eight subjects participated in the picture condition.

Apparatus

Apparatus was identical with calibration experiment 1.

Materials

The sets of 8 items were chosen from the set of 20 items originally constructed for the first calibration experiment. With the picture materials, 8 items were selected by 2 independent raters to be the least confuseable with one another. With the CVC materials, 8 CVC's were chosen which differed in their orthography so as not to be confuseable with one another. The chosen CVC's were "FAP, MEF, GAK, DEZ BUP, SUZ, KAX, TOZ."

Procedure

Design of the experiment was similar to the first calibration study with the following changes. The set of materials from which the memory load stimuli were drawn was reduced from 20 items to 8 items. The 8 possible items in the CVC and picture condition were combined into randomly drawn sets of 1, 3, 4, and 5 items. All other aspects of the experimental design were identical to calibration experiment 1. Instructions were also identical to calibration experiment 1.

Results

Accuracy Analysis

Accuracy is plotted in Figure 13 and presented in Table 3 in percent correct on the memory probe tasks across load.

	Memory Load			
Task	1	3	4	5
Digit	99	--	98	98
CVC	92	93	86	76
Picture	94	85	77	71

Table 3: Calibration Experiment 2 - Accuracy on Memory (Percent Correct)

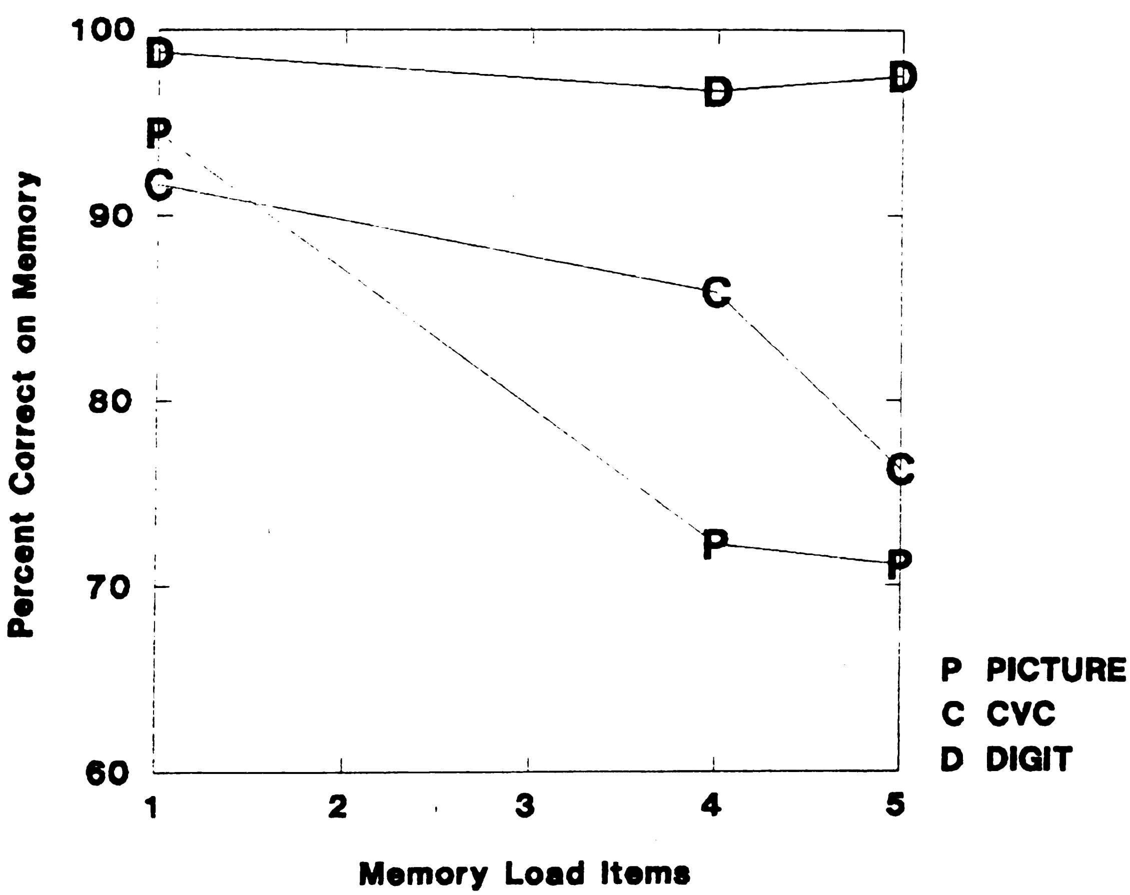
There is not a noticeable improvement in accuracy over the results of the first calibration experiment. Subjects in the 1 item condition are still performing at over 90% correct in all tasks. There are still differences in accuracy at high loads.

Insert Figure 13 about here

Error rates were subjected to an analysis of variance with the 3 tasks as a between subjects factor and 3 of the 4 different load conditions as a within subjects factor. Because the digit task does not have a 3 item load condition, this condition was dropped from the analysis. The other option for the analysis was to ignore the load effects and include all accuracy data, but this option was not chosen as it might have lead to a more severe distortion of the data than simply dropping a category of observations. There is a significant decline in percent correct with increasing load evident in the significant main effect of load [$F(2,60) = 34.169, p < 0.0001, MSE=43$]. There is also a significant difference between tasks in percent correct evident in the significant main effect of task [$F(2,30) = 13.556, p < 0.0001, MSE=188$]. There is also a significant interaction between load and task [$F(4,60) = 8.868, p < 0.0001, MSE=43$]. This is evident in Figure 13 where percent correct for the CVC and Picture tasks declines across load much more rapidly than percent correct in the digit task.

The significant load by task interaction in the accuracy data was further explored with one way ANOVA's as simple effects tests. The decline in percent correct in the digit task was not significant [$F(1,11)=1.320, p > 0.05, MSE=7$]. The decline in percent correct in the CVC task was significant across load [$F(1,11)=18.209, p < 0.001, MSE= 78$]. The decline in percent correct in the picture task was significant across load [$F(1,8)=32.667, p < 0.0001, MSE=75$].

Calib. Exp. #2 - Accuracy on Memory



These tests confirm that the load by task interaction was due to a significant decline in percent correct across load for the CVC and picture tasks but not for the digit task.

Tone Latency Analysis

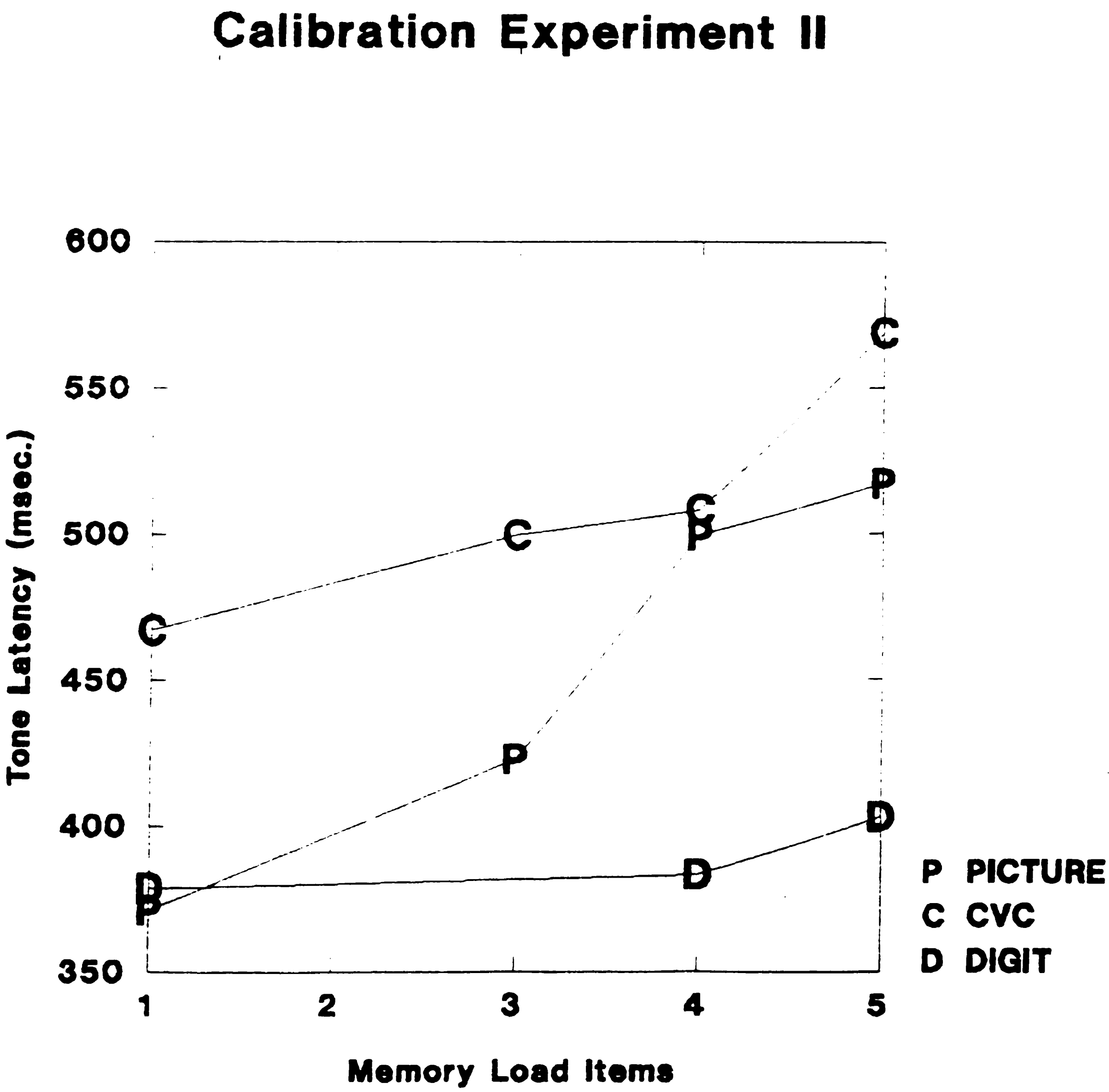
In Figure 14 the tone detection latencies for trials where memory responses were correct from the second versions of the CVC and picture tasks are plotted along with the tone latencies from the first version of the digit task, collected in calibration experiment 1. These numbers also appear in Table 4.

Insert Figure 14 about here

		Memory Load		
Task	1	3	4	5
Digit	388	---	401	437
CVC	467	499	508	569
Picture	371	422	499	517

Table 4: Calibration Experiment II Tone Latencies (ms.)

Once again to determine if the effect of load on tone detection latency was comparable across the three tasks, a repeated measures analysis of variance was performed on average tone latencies with the 3 tasks as a between subjects factor and only 3 of the 4 different load conditions as a within subjects factor; the 3 item



Calibration Experiment II
600
550
500
450
400
350
Tone Latency (msec.)
1
2
3
4
5
Memory Load Items
P PICTURE
C CVC
D DIGIT

load condition was dropped from the latency analysis for the same reason it was dropped from the error analysis.

The ANOVA revealed no significant difference in the size of the load effect across tasks in that the main effect of task was not significant [$F(2,29) = 2.377, p > 0.05, MSE=51495$]. Overall, tone detection latencies did significantly increase as load increased in that there was a significant main effect of load [$F(2,58)= 14.384, p < 0.0001, MSE=4120$] In Figure 14, the main effect of load is seen in the graph of the average tone latency in the three tasks across load items. The interaction between task and load is not significant, but marginally so [$F(4,58) = 2.409, p = 0.059, MSE=4120$].

Trials With Memory Load Errors

In order to further justify the discarding of trials in which there is an error in the subjects' responses to the memory load were incorrect, tone latencies were determined for those trials. It should be noted that the number of observations within each condition is small, and furthermore that there were not observations in all cells of the design for all subjects. This makes inferential analysis of these results impractical. Despite these problems, this aspect of the data remains interesting, as the question of interest was what happens to tone latency when subjects fail to protect their memory loads? Tone latencies for trials in which there were memory errors are plotted for each task in Figure 15.

Insert Figure 15 about here

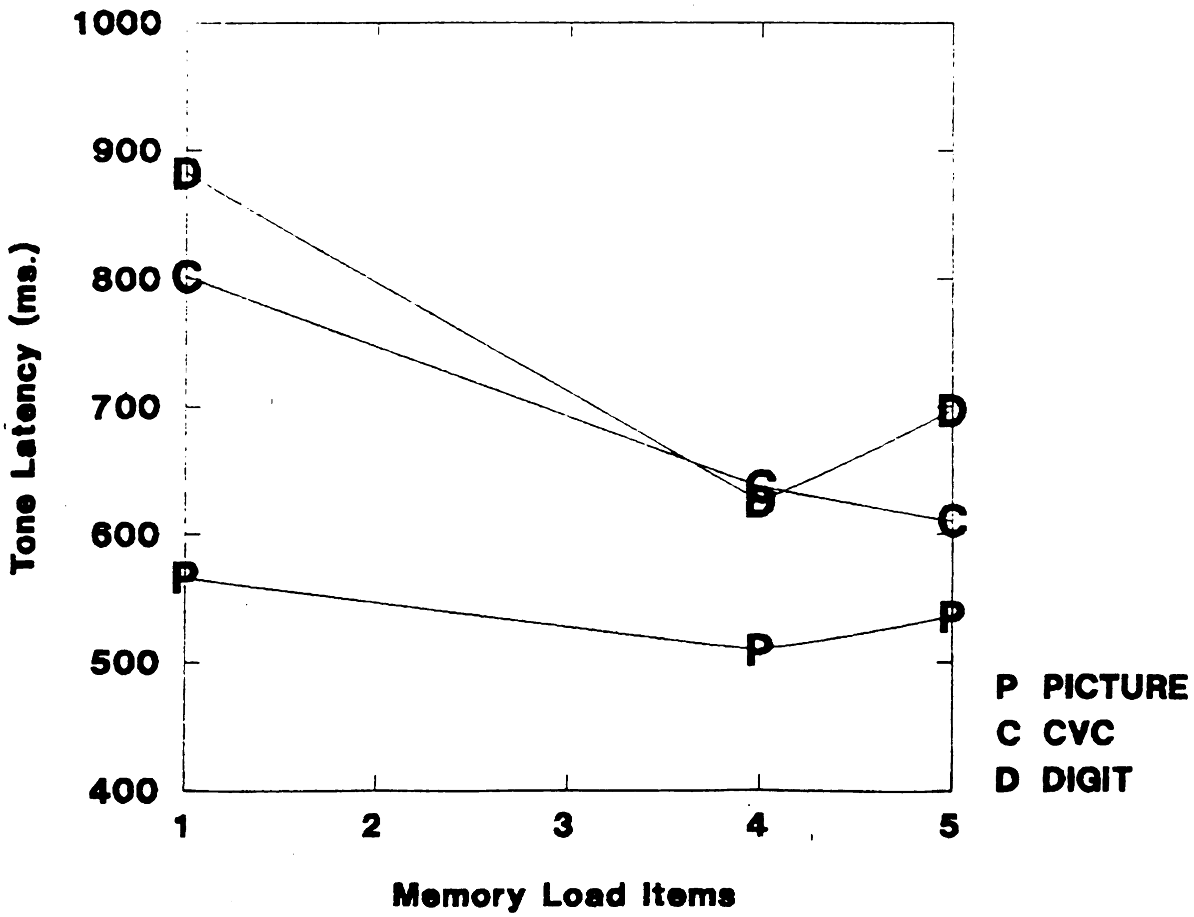
The important aspect of this graph is that tone latencies decline across increasing memory load, where in the trials in which memory loads were protected, depicted in Figure 14, tone latencies increased with increasing memory load. Tone latencies in Figure 15 are also noticeably higher across the board then on trials for which memory responses were correct.

Discussion

The possibility of a type II error in this situation warrants caution in the interpretation of these results. The interaction between load and task is not significant but there were not many subjects in the calibration experiment. It is apparent in Figure 14 that there is a trend towards non-equivalence among the three tasks, even though the interaction is non-significant. Specifically, this is a problem because the results of the naming experiment would be difficult to interpret with any confidence if the attention demands of the tasks are not known in advance; which was specifically the purpose for the calibration experiments.

One of the two desired objectives was achieved in the second calibration experiment. There is no evidence for a shift in attention from the memory task to the tone task in the highest load condition. In Figure 14, it can be seen that tone detection latencies increase smoothly as load increases. However, there is no

CS-II Trials W/ Memory Load Errors



improvement in accuracy on the memory task over the first calibration experiment.

Based on the results of the two calibration experiments, it seems unlikely that it is possible to equate the three memory tasks in terms of attention demand, as measured by tone detection latency. There is no point at which the tone latencies of the CVC and picture conditions match the latencies for the digit condition at high memory loads. Therefore, it was judged that further manipulation of these three tasks to achieve equivalence would be pointless.

Since equivalence of attention demand was not possible, the 1 and 5 item loads were chosen for all 3 tasks so that equivalence of memory load would be achieved. Although equivalence among the three tasks was not achieved in the calibration experiments, it was confirmed that all three tasks exhibit an increase in tone latency with increasing memory load. Furthermore, if the tone latencies are reliable indicators of the relative attention demands of the three tasks they may be of some use interpreting the results of the naming experiments. That is, it can be said from the results of these experiments that the digit task represents the lowest of the three attention demands, and the CVC and picture tasks represent higher attention demands. If the results obtained by Paap and Noel (1991) are due to attention demand, it is most likely that they will show up in the CVC and picture conditions, as these conditions exhibit the highest attention demand in the high load conditions. Finally, discarding trials in which there are memory load errors is justified by the appearance of a different pattern of naming latencies in these trials. Again, it appears that there is not evidence for a tradeoff between memory and tone latency because overall subjects were much slower on tone latency when they made memory errors.

Chapter III
Naming Experiment

The purpose of the naming experiment was to determine if the speeded naming of low frequency exception words and the slowed naming of the other three types of words under load observed by Paap and Noel (1991) was due to handicapping of the rule-governed or assembled phonological processing by reduced capacity, as they suggest, or due to cross-talk between phonological units. This naming experiment as originally conceived consisted of three memory load tasks and a single set of naming stimuli from Taraban and McClelland (1987). An additional set of naming stimuli, from Paap and Noel (1991) was included when it became available. An additional memory load task was also included after the experiment had begun.

This fourth memory load task, which used high frequency nouns as memory stimuli, was added after preliminary analysis of the data indicated that the presence of high frequency words as the memory load might be necessary to obtain the pattern of results reported by Paap and Noel. (The exact nature of these indications will be discussed with the results of the naming experiment.) Consequently, a set of 8 single syllable nouns with frequencies comparable to the digit name frequencies were chosen from the Kucera and Francis (1967) norms. When the noun task was added, it was predicted that it would show the same pattern of naming latencies which Paap and Noel observed using digits.

To best serve the purpose of this experiment, the additional conditions were included as a part of the main experiment, even though they were conceived of after the inception of the main experiment. Analyzing the data from all 8 conditions together best answers the original question: what causes the pattern of naming latencies originally observed by Paap and Noel?

The predictions including the fourth task and the second set of naming stimuli were that if the Paap and Noel results were due to attentional interference, all four memory tasks should exhibit the pattern of naming latencies they found since all four tasks are attention demanding (assuming that the attention demands of the noun task resemble those of the digit, CVC, and picture tasks -- though plausible, it should be noted that the noun task was not calibrated). If the Paap and Noel results were due to phonological-articulatory interference, their pattern should not appear in the task which does not involve articulation, the picture condition. If the results do depend on phonological-articulatory interference, and the interference is specifically with the OPC route's assembly of phonology, then Paap and Noel's pattern should appear most clearly in the CVC condition. Alternatively, if the results depend on the presence of high frequency words as a memory load, the results should only appear in the tasks which use high frequency words as memory stimuli, the digit task and the noun task. Since both sets of naming stimuli consist of high and low frequency, consistent and exception words, of comparable frequencies, it was also predicted that performance on the two sets of naming stimuli would not differ significantly. If the two sets of naming stimuli did produce different results, then one would suspect that Paap and Noel's phenomenon is controlled by possibly quite subtle properties of spelling-to-pronunciation patterns or word neighborhood organization.

Method

Subjects

One hundred and ninety two undergraduate psychology students enrolled in introductory psychology classes at Michigan State University participated for partial fulfillment of class requirements, twenty-four subjects in each of the eight conditions. Participation was restricted to native speakers of English. The data from one subject (in the picture condition with the Taraban & McClelland naming stimuli) was discarded when it became apparent that this subject was not following directions for the memory task (Almost all responses for when the target was absent were incorrect).

Apparatus

All stimuli were presented and all responses were collected using an Apple MacIntosh Plus computer with a Gerbrands model G-1341 voice activated relay attached to the Macintosh through the mouse port. A Sure model number 5755 microphone placed on a microphone stand was attached to the voice activated relay. The presentation of stimuli and the recording of all reaction times was controlled by the PsychLab program, version 0.97, developed by Teren Gum and Daniel Bub at McGill University (1988). The experimental sessions were recorded on a Sharp model RD465AV1 desktop cassette tape recorder using a Realistic catalog number 33-1063 tie-pin microphone which the subjects wore on a cord around their necks, except in the noun condition where the tie-pin microphone was attached to the stand microphone.

Materials

Materials for the eight conditions consisted of two sets of naming stimuli and four sets of memory load stimuli. Details were as follows:

Naming Stimuli

One set of naming stimuli were from Paap and Noel (1991) and the second set of naming stimuli were from Taraban and McClelland (1987). Both sets of stimuli consisted of four categories of words: high and low frequency, consistent and exception words. The Paap and Noel stimuli consisted of 20 words in each of the four categories while the Taraban and McClelland stimuli consisted of 24 words in each of the four categories. The frequencies of the categories of words are roughly comparable, with the exception of high frequency consistent (HFC) words, statistics for this are reported in Table 5. A complete listing of the stimuli appears in Appendix D.

Paap and Noel Stimuli

	HFE	HFC	LFE	LFC
Mean	1440	279	13	13
Median	640	223	7	9
Standard Dev.	2724	279	16	13

Taraban and McClelland Stimuli

	HFE	HFC	LFE	LFC
Mean	1566	1154	41	21
Median	590	469	17	16
Standard Dev.	2633	1628	59	13

Table 5: Kucera and Francis (1967) Frequencies For Naming Stimuli

Naming stimuli in all conditions appeared in black lower-case 24 point geneva type on a white background.

Memory Load Stimuli

The memory load stimuli described in the calibration experiments were used in the naming experiments with a change in the CVC condition. This makes the calibration data on this task invalid. It may be a plausible assumption that the change in the task would not alter its attention demands -- but this assumption remains untested. The change was made because subjects in the calibration experiments reported that they could use the first letter of the nonsense syllable to remember them instead of reading the entire CVC, new nonsense syllables were selected from the Underwood and Schulz (1960) norms. These nonsense syllables were rated low in sensibility and were similar in orthography to the names of the digits used in the digit task (with the exception of the digit name "eight" which does not begin with a consonant). In addition, the first letters of some of the CVC's are identical, to encourage subjects to read and remember the entire CVC. They were the following eight: WUC, TOV, TIV, FUP, FOY, SEB, TEF, NID.

A noun condition was added as a fourth memory task. Eight high frequency, four letter, one syllable nouns were selected from Kucera and Francis (1967) to serve as memory load stimuli. The nouns were WAY, TIME, THING, FACT, FORCE, STATE, AGE, and NAME. They were chosen so that the initial sounds were roughly similar to the sounds of the digit names ONE, TWO, THREE, FOUR, FIVE, SIX, EIGHT, and NINE. The frequencies of the nouns were matched to the frequencies of the digit names as reported in Kucera and Francis (1967). Mean frequency of the nouns is 824.5 and mean frequency of the digit names is 726.4.

Both the noun and CVC stimuli for the memory task were presented in uppercase black 24 point geneva type centered on a white background. The typeface for the noun stimuli was changed. The noun stimuli were presented in bold uppercase black 18 point helvetica type. The typeface was made smaller so that all the nouns would fit on the screen at once. The nouns were presented in bold type because pilot subjects, the data from which is not reported in this paper, exhibited confusion between the naming and memory parts of this task. Changing the memory stimuli to bold type alleviated this confusion. Bold type was not used for the memory load stimuli in the CVC and digit conditions, which were run before the noun condition, as this confusion was not evident.

Procedure

Subjects were individually tested in a small closed temperature controlled room with black walls, a black ceiling, a black floor, overhead fluorescent lighting, and two tables, one of which held the apparatus. Subjects were seated in front of the Macintosh at a distance which varied between approximately 2 and 3 feet. Under these conditions, the visual angle subtended by a four letter 18 point stimulus varied from 1 degree 0 minutes to 1 degree 30 minutes, and the visual angle subtended by a four letter 24 point stimulus varied from 1 degree 47 minutes to 1 degree 12 minutes.

Different groups of 24 subjects participated in each of the 8 memory load tasks with half of the subjects in each condition receiving a different half of the word list under high and low load. The list of naming stimuli was randomized and split in half before being combined with memory load stimuli. The half of the list of naming stimuli that was named under low and high loads was switched on half of the lists. To avoid artifacts due to a particular word always being presented with a particular set of memory stimuli, four different random pairings of the naming stimuli with the memory stimuli were constructed; six subjects received each of these lists. Trials were presented in a new random order for each subject, with the constraint that no more than 4 trials of the same type occurred in a row.

Subjects were told that the memory task was the primary task and that a secondary task would co-occur with it, the naming task. They were told that the naming task was intended to distract them from the memory task but they should try to name the words clearly, loudly, and as quickly as possible. Subjects were also told that they could take as long as necessary to respond to the memory probe and to be as accurate as possible. There was no error feedback given during the trials but the experimenter did ask the subjects to speak louder when they failed to trigger the voice activated relay. A copy of the instructions read to the subjects is presented in Appendix E.

A trial began with the visual presentation of a fixation point for a duration of 1000 ms. which was in turn followed by the presentation of one or five randomly selected items for the memory load task. In a departure from Paap and Noel's (1991) procedure, which was also done in the calibration experiments, the times the study set remained on the screen were adjusted for the number of items presented and the kind of material. For the digit condition, items appeared for 400 ms. each; that is, the one item set was displayed for 400 ms. and the five item set was displayed for 2,000 ms. For the picture, CVC, and noun conditions, items were presented for 800 ms. each; that is, the one item sets were displayed for 800 ms. and the five item sets were displayed for 4,000 ms. Adjustment of study times were done in this manner to avoid the items in 1 item sets being studied longer and thus being more familiar to the subjects than the items in the 5 item sets.

The naming stimulus appeared following a delay which varied between 1 and 2 seconds (at quarter second intervals) after the offset of the memory set, during which time a blank screen was displayed. The randomness of the delay was intended to eliminate any planned switching of attention to the naming task. The naming stimulus remained on the screen until the subject responded (there was a 2,000 ms. deadline for the naming task, after which a null response would be recorded and the trial would be discarded). After the response or the expiration of the deadline a blank screen was displayed until 4 seconds plus the naming latency had elapsed from the offset of the memory set. This blank screen was followed by the presentation of the memory probe item which remained until the subject responded. Subjects responded by either pressing the "/?" key, which was marked "yes",if the item had appeared in the study set or by pressing the "zZ" key, which was marked "no",if the item had not appeared in the study set. An inter-trial interval of 3 seconds elapsed between the memory response and the beginning of the next trial.

There was a slight difference in the timing between these experiments and the Paap and Noel experiments due to limitations in the PsychLab program. Memory retention intervals were extended by subjects' naming latencies in these experiments, unlike the Paap and Noel experiments. This means that the retention interval will be extended by about 600 ms. - to a maximum of 2,000 ms., the length of the naming latency. This time extension may have decreased memory performance but was not thought to be important in this investigation because naming latencies were of primary interest.

Subjects initially read the instructions silently along with the experimenter who read them aloud. Eight practice trials were then completed by the subject, four with a one item load and four with a five item load, presented in a random order. These practice trials used memory load stimuli identical to those used in the experimental trials and naming stimuli which did not appear in either the Paap and Noel or Taraban and McClelland lists of naming stimuli. The subject then waited for approximately two minutes while the stimuli for the experimental trials were loaded and randomized by the PsychLab program. Unbeknownst to the subjects, the experimental trials began with four filler trials which were discarded in the data analysis. The number of experimental trials then depended upon the list of naming stimuli: 80 experimental trials with the Paap and Noel stimuli or 96 experimental trials with the Taraban and McClelland stimuli. The experimental trials took subjects about 15-20 minutes to complete in the digit task and about 20-25 minutes to complete in the CVC, picture, and noun tasks. Subjects were debriefed following the completion of the experimental trials. The entire experiment session lasted about 30 minutes.

Results

The 8 conditions in this experiment were varied between subjects. The four types of memory load stimuli (digits, nouns, CVC's, and pictures) were completely crossed with the two types of naming stimuli (those from Paap and Noel and those from Taraban and McClelland). The overall analysis of variance for all 8 conditions combined will be reported followed by explorations of significant interactions. Because of the theoretical importance of the slowdown in the naming of low-frequency exception words, planned comparisons will be reported for this effect regardless of significance in the ANOVA.

Error Detection and Removal

Naming latencies are reported for correct trials only. Trials were discarded if there were memory errors, false starts, mispronunciations, or environmental noises. Those naming latencies longer than 2,000 ms. were considered null responses by the PsychLab program and those 125 ms. or lower were regarded by the experimenter as voice key triggering errors. This figure of 125 ms. is comparable to cutoffs used by other investigators (125 ms. -- Taraban and McClelland, 1981; 120 ms. -- Paap and Noel, 1991). The means of the correct trial naming latencies for each of the four types of naming stimuli at high and low memory loads are presented in Table 6 and Figure 16 A&B.

Insert Table 6 and Figure 16 A&B About Here

False starts, mispronunciations, and environmental noises were determined by judges listening to audio tapes of the experiment sessions. As three separate raters were involved in the transcription of naming errors, with each tape scored by only one rater, percent agreement between the raters was determined for 4 arbitrarily selected tapes. There was 93.75% agreement between raters 1 and 2, 94.69% agreement between raters 1 and 3, and 96.88% agreement between raters 2 and 3. As agreement between raters was high, combining ratings from the three different raters was deemed acceptable; that is, it was not necessary for all raters

T&M Digit Task

Load	HFE	HFC	LFE	LFC
1	701	690	742	715
5	703	709	739	697
Diff.	-2	-19	+3	+18

P&N Digit Task

Load	HFE	HFC	LFE	LFC
1	720	733	862	770
5	727	726	837	797
Diff.	-7	+7	+25	-27

T&M Noun Task

Load	HFE	HFC	LFE	LFC
1	750	753	826	766
5	787	772	840	814
Diff.	-37	-19	-14	-48

P&N Noun Task

Load	HFE	HFC	LFE	LFC
1	728	723	863	768
5	769	756	820	786
Diff.	-41	-33	+43	-18

T&M CVC Task

Load	HFE	HFC	LFE	LFC
1	721	716	788	739
5	741	777	783	792
Diff.	-20	-58	+5	-53

P&N CVC Task

Load	HFE	HFC	LFE	LFC
1	728	731	807	773
5	775	738	844	771
Diff.	-47	-7	-37	+2

T&M Picture Task

Load	HFE	HFC	LFE	LFC
1	729	710	790	760
5	759	769	827	767
Diff.	-30	-59	-37	-7

P&N Picture Task

Load	HFE	HFC	LFE	LFC
1	715	687	780	749
5	709	725	830	775
Diff.	+6	-38	-50	-26

Table 6: Naming Latencies (ms.)

Figure 16(A) - Naming Latencies
Paap & Noel Stimuli

Key:
X High Frequency Exception
C High Frequency Consistent
x Low Frequency Exception
c Low Frequency Consistent

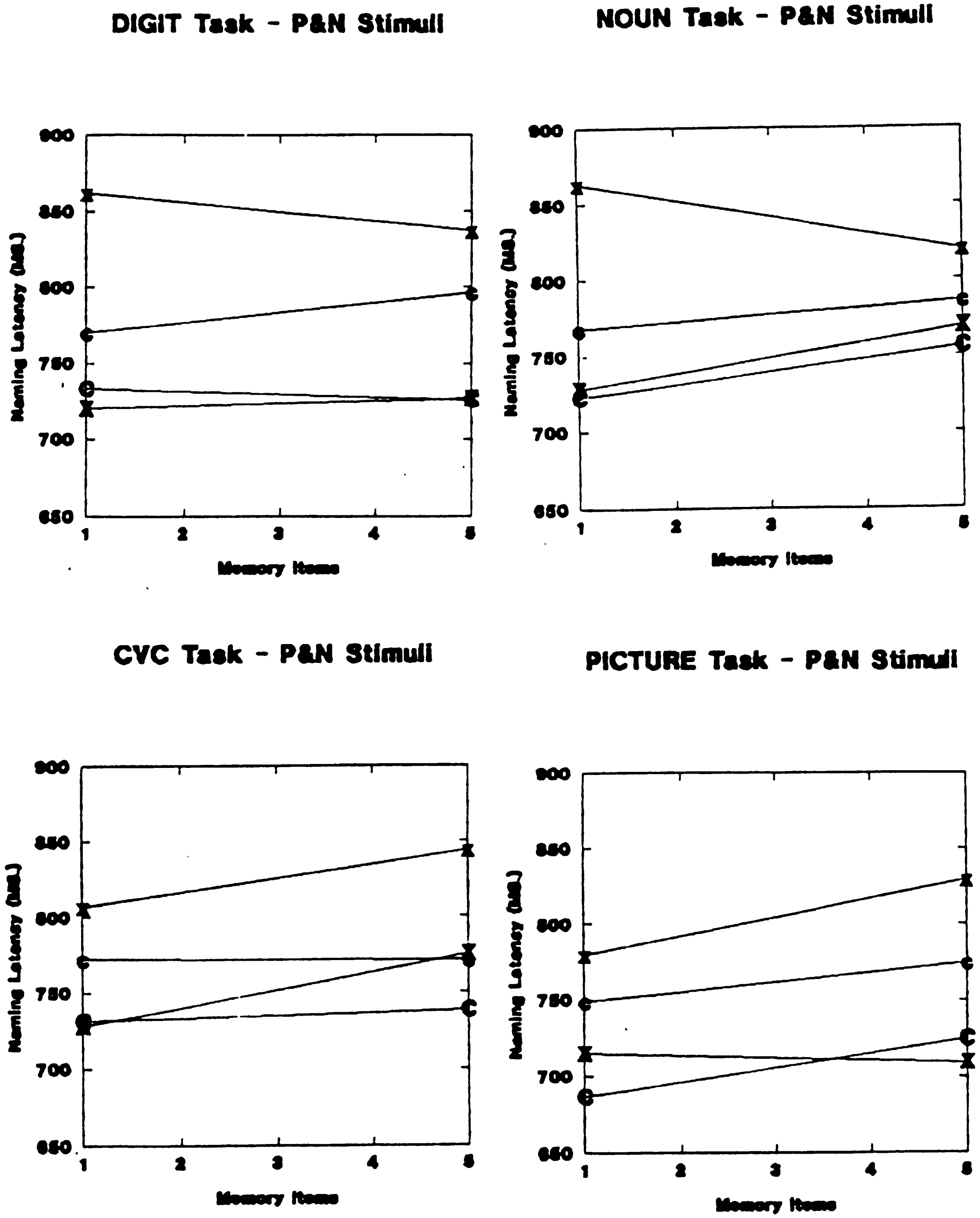
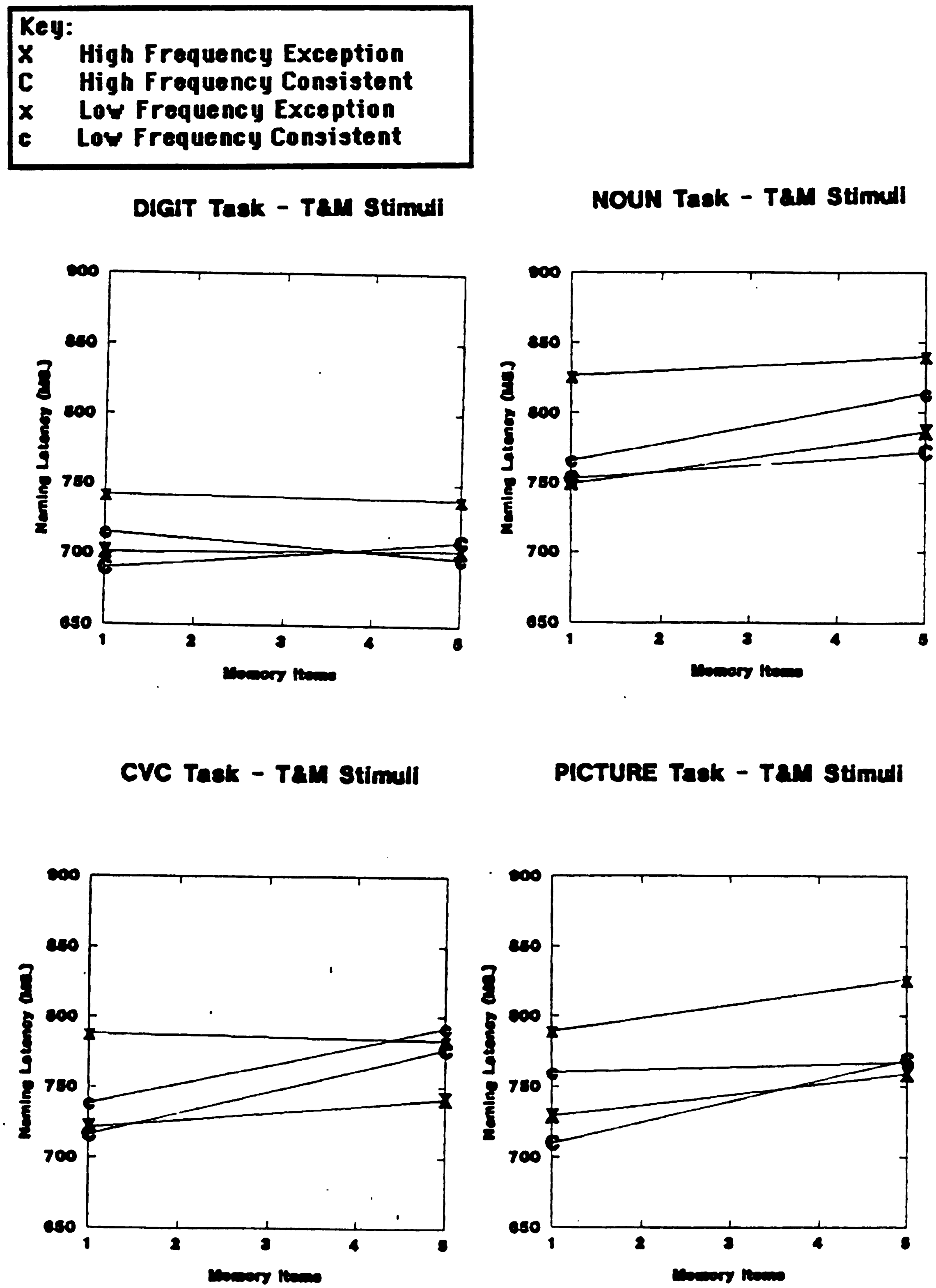


Figure 16(B) - Naming Latencies
Taraban & McClelland Stimuli



to score all tapes. A summary of the frequency of these errors is presented in Table 7.

Insert Table 7 About Here

Analysis of Memory Errors

Memory errors, the most frequent of the error types reported in Table 7, were subjected to further analysis, to look for effects of load and task on the memory error rates. Accuracy on memory for the three types of memory load stimuli plotted for each of the two sets of naming stimuli in Figure 17. A 4 x 2 x 2 x 2 x 2 analysis of variance with the between subjects factors task and stimuli and repeated measures on frequency, consistency, and load was performed on the memory accuracy scores. There was not a significant difference in accuracy across the two sets of naming stimuli [$F(1,183) = 0.478, p > 0.05, MSE=81$]. There was a significant difference in accuracy among the three memory tasks [$F(3,183)=39.709, p < 0.0001, MSE=81$]. There was a significant decrease in accuracy with increasing memory load [$F(1,183)=302.364, p < 0.0001, MSE=46$]. This decrease in accuracy with increasing memory load differed significantly among the three tasks, as seen in the significant effect for the interaction of load and task on accuracy [$F(3,183)=52.681, p < 0.0001, MSE=46$]. No other interactions approached significance.

Table 7:
Percent Totals - Errors by Condition and Memory Load

Taraban & McClelland Stimuli

Memory Load = 1 Items

	Err 1	Err 2	Err 3	Err 4	Err 5	Total
Digit	1.258	2.300	0.304	0.043	0.521	4.427
CVC	2.865	1.345	0.304	0.217	1.128	5.859
Picture	2.853	1.178	0.453	0.045	0.317	4.846
Noun	3.125	0.521	0.608	0.260	0.651	5.165

Memory Load = 5 Items

	Err 1	Err 2	Err 3	Err 4	Err 5	Total
Digit	2.127	1.996	0.304	0.130	0.998	5.556
CVC	10.069	1.476	0.738	0.130	0.911	13.325
Picture	13.089	1.495	0.498	0.272	0.362	15.716
Noun	5.295	0.868	0.651	0.174	0.608	7.639

Paap & Noel Stimuli

Memory Load = 1 Items

	Err 1	Err 2	Err 3	Err 4	Err 5	Total
Digit	2.240	3.125	1.198	0.365	0.625	7.552
CVC	2.500	0.885	0.885	0.052	0.000	4.329
Picture	2.083	0.938	1.042	0.052	0.208	4.323
Noun	1.875	0.625	1.823	0.208	0.718	5.313

Memory Load = 5 Items

	Err 1	Err 2	Err 3	Err 4	Err 5	Total
Digit	2.208	3.281	1.458	0.417	0.156	7.396
CVC	11.250	0.885	1.250	0.052	0.156	13.594
Picture	14.375	0.729	1.250	0.260	0.104	16.719
Noun	6.250	0.677	1.250	0.417	0.885	9.479

Key to Error Types

1 Memory Error
2 Skipped naming, naming too low
3 Mispronunciation
4 False Start
5 Noise, Voice key triggering error

Naming latencies for trials in which there were memory errors are plotted in Figure 17 A&B. Also, it should be noted that the means plotted in Figure 17 A&B are from trials with memory errors, but without false starts and mispronunciations removed. There were not enough observations to allow inferential analysis of this data. However, the pattern of tone latencies in Figure 17 A&B in large part resembles the pattern of tone latencies in Figure 16 A&B, suggesting that there is not an inverse relationship between accuracy in the memory task and speed in the naming latency task.

Insert Figure 17 A&B About Here

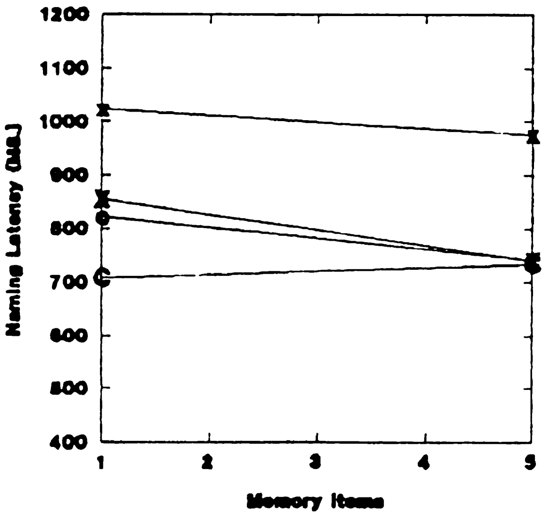
Results of the overall ANOVA on Naming Latencies

A 4 x 2 x 2 x 2 x 2 analysis of variance with the between subjects factors task and stimuli and repeated measures on frequency, consistency, and load was performed on the naming latencies. The main effects of the between subjects factors task and stimuli were not significant [$F(3,183) = 1.350, p=0.260$, $MSE=83362$ and $F(1,183) = 0.535, p=0.466, MSE=83362$ respectively]. There was a significant main effect of frequency [$F(1,183) = 210.180, p < 0.0001$, $MSE=5369$] in that high frequency words were pronounced faster than low frequency words (734 vs.788 ms. respectively). There was a significant main effect of consistency [$F(1,183) = 70.683, p < 0.0001, MSE=3237$] in that consistent words were pronounced faster than exception words (748 vs. 777 ms. respectively).

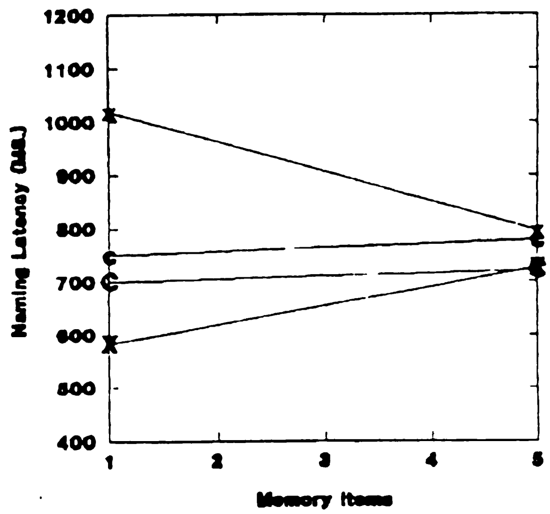
Figure 17(A) - Naming Latencies
Trials With Memory Errors
Paap & Noel Stimuli

Key:
- X High Frequency Exception
- C High Frequency Consistent
- x Low Frequency Exception
- c Low Frequency Consistent

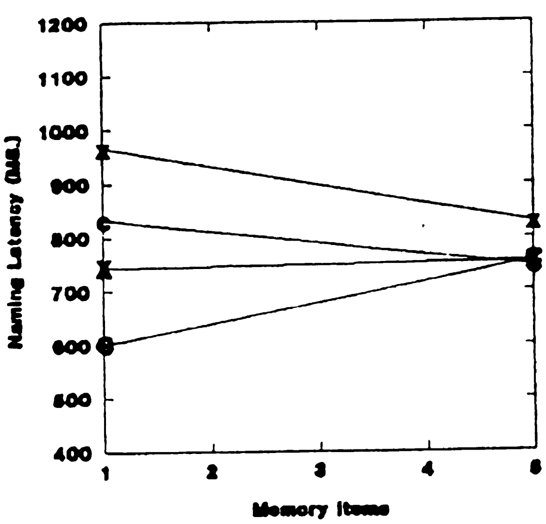
P&N DIGIT Task W/ Memory Errors



P&N NOUN Trials W/ Memory Errors



P&N CVC Trials W/ Memory Errors



P&N PICTURE Trials W/ Memory Errors

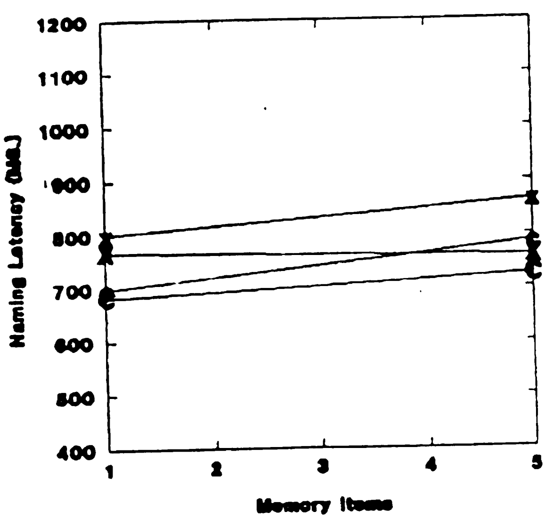
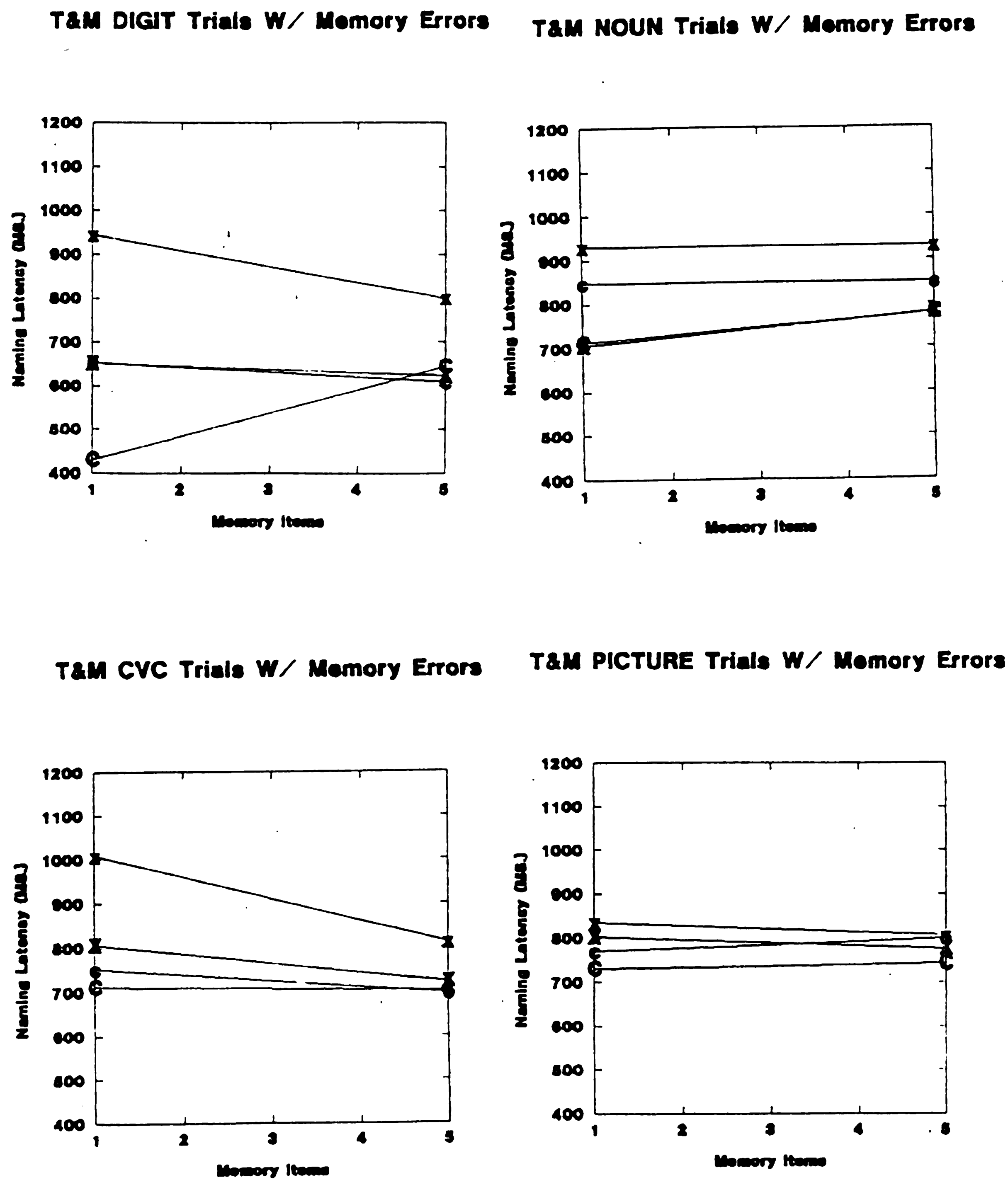


Figure 17(B) - Naming Latencies
Trials With Memory Errors
Taraban & McClelland Stimuli

Key:
X High Frequency Exception
C High Frequency Consistent
x Low Frequency Exception
c Low Frequency Consistent



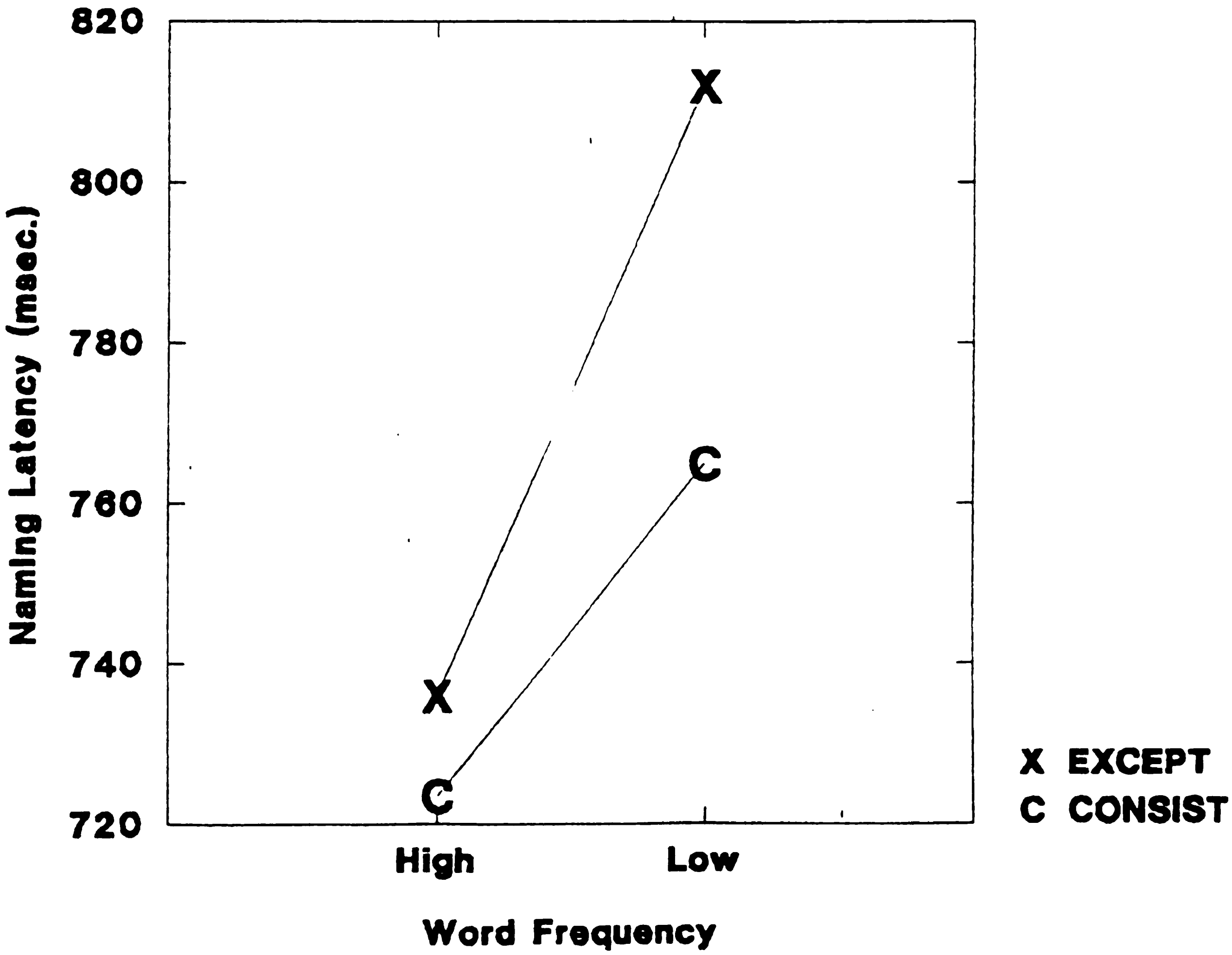
The main effect of load was also significant [$F(1,183) = 22.805, p < 0.0001$, MSE=6438] in that words under low load were pronounced faster than words under high load (751 vs. 771 ms. respectively).

The interaction of frequency and consistency was significant [$F(1,183) = 54.762, p < 0.0001$, MSE=3228] in that the naming of exception words slowed across decreasing frequency (76 ms.) more than the naming of consistent words slowed across decreasing frequency (33 ms.) This interaction is graphed in Figure 18.

Insert Figure 18 About Here

The interaction of frequency, consistency, and load, which was predicted according to the Paap and Noel results, was not significant in the overall analysis. However the interaction of frequency, consistency, and load with task was significant [$F(3,183)=4.167, p < 0.01$, MSE=3737]; this significant interaction will be explored further after the results of the overall ANOVA have been fully reported.

The two sets of stimuli appear in Figure 16 A&B to be acting quite differently, but the differences between them were in fact subtle. There was neither a main effect of stimuli nor any significant interactions involving stimuli with either load and task [although the three way interaction of frequency, task and stimuli did approach significance, $F(3,183) = 2.3543, p = 0.074$, MSE=5369]. Thus, for the purposes of testing hypotheses about capacity demands and crosstalk interference, the two sets of stimuli appear to have behaved similarly. However, Frequency * Consistency Interaction



stimuli did interact significantly with frequency [$F(1,183) = 20.195, p < 0.0001$, MSE=5369] in that the frequency effect with the Paap and Noel stimuli (71 ms.) was larger than the frequency effect with the Taraban and McClelland stimuli (37 ms.). Stimuli also interacted with consistency [$F(1,183) = 5.952, p < 0.05$, MSE=32375] in that the slowdown in naming latency for high vs. low frequency words was larger with the Paap and Noel stimuli (31 ms.) than with the Taraban and McClelland stimuli (17 ms.). Thus, the Paap and Noel stimuli provide larger effects of frequency and larger effects of consistency; therefore, they may in fact be better stimuli to rely upon when looking for an interaction of frequency, consistency, and load, despite the absence of significant interactions between stimuli and either load or task.

Exploration of the F*C*L*T interaction

Because the interaction of frequency, consistency, load and task was significant in the overall analysis, the three way interaction of frequency, consistency, and load was examined in each of the tasks by collapsing across the two sets of stimuli with a separate analysis of variance performed for each task. Although the two sets of stimuli appeared to be acting differently in Figure 16 A&B, collapsing across the two naming stimuli sets, as seen in Figure 19 and Table 8, was justified by the lack of a main effect of stimuli and the lack of any significant interactions involving the factors stimuli and either load or task together.

Insert Figure 19 and Table 8 About Here

Digit Task

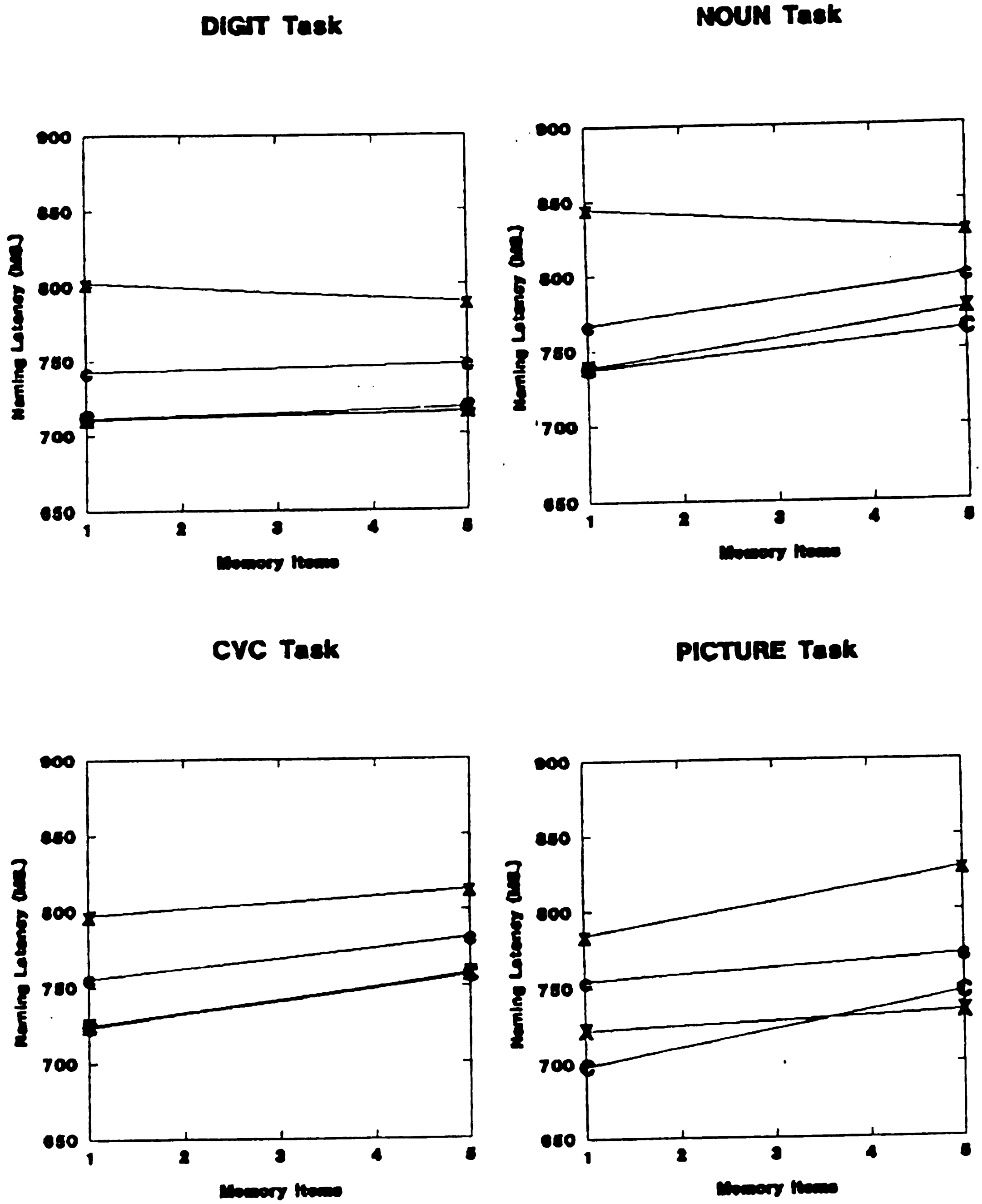
The predicted pattern of results appears with the digit task but was not significant in that there was not a significant interaction of frequency, consistency, and load [$F(1,47) = 0.544, p > 0.05, MSE = 2933$]. There was a significant main effect of frequency [$F(1,47)=41.707, p < 0.0001, MSE=7324$] in that the high frequency words were pronounced faster than the low frequency words (714 vs. 770 ms. respectively). There was also a significant main effect of consistency [$F(1,47)=15.354, p < 0.0001, MSE=3667$] in that the consistent words were pronounced faster than the exception words (730 vs. 754 ms. respectively). The main effect of load was not significant.

The only significant interaction was the frequency by consistency interaction [$F(1,47)=21.061, p < 0.0001, MSE=3070$] in that the naming of exception words slowed across decreasing frequency (82 ms.) more than the naming of consistent words slowed across decreasing frequency (30 ms.).

Because the speeded naming of low frequency exception words under load and slowed naming of other types of words was of great interest, a series of four matched pairs t-tests were performed to look for significant changes in naming each of the word types across load in the digit condition; that is, the changes in each line appearing in Figure 19. The predicted speedup in the naming of low

Figure 19 - Naming Latencies
Both Sets of Naming Stimuli

Key:
X High Frequency Exception
C High Frequency Consistent
x Low Frequency Exception
c Low Frequency Consistent



Digit Task
Word Type

Load	HFE	HFC	LFE	LFC
1	711	712	802	743
5	715	717	788	747
Diff.	-4	-5	+14	-4

Noun Task
Word Type

Load	HFE	HFC	LFE	LFC
1	739	738	845	767
5	778	764	830	800
Diff.	-39	-26	+15	-33

CVC Task
Word Type

Load	HFE	HFC	LFE	LFC
1	725	724	797	756
5	758	758	813	782
Diff.	-33	-34	-16	-26

Picture Task
Word Type

Load	HFE	HFC	LFE	LFC
1	722	698	784	754
5	734	746	828	771
Diff.	-12	-48	-44	-17

Table 8: Naming Latencies collapsed across stimulus lists.

frequency exception words does appear (4 ms.), but it is not significant. The 6 ms. slowdown in the naming of high frequency consistent words was not significant. The 4 ms. slowdown in the naming of low frequency consistent words was not significant. Finally the 14 ms. speedup in the naming of high frequency exception words was not significant.

Digit Replication of Paap and Noel

Though stimuli did not interact with load or task, a separate set of tests was performed on the digit task naming latencies for Paap and Noel's stimuli just to see if the most direct replication of their experiment produced their pattern of results in significant form. The predicted interaction of frequency, consistency, and load was marginally significant [$F(1,23) = 3.912, p = 0.06, MSE=3243$]. The main effect of frequency was significant [$F(1,23) = 102.957, p < 0.0001, MSE=3777$] in that high frequency words were pronounced faster than low frequency words (727 ms. vs 817 ms. respectively). The main effect of consistency was also significant [$F(1,23) = 10.820, p < 0.01, MSE= 3971$] in that consistent words were pronounced faster than exception words (757 ms. vs 787 ms. respectively). The main effect of load was not significant. The frequency by consistency interaction was significant [$F(1,23)=26.569, p < 0.0001, MSE=2342$].

A series of four planned matched pairs t-tests were performed to look for significant changes in naming each of the word types across load; that is, the changes in each line appearing in Figure 19. The 25 ms. speedup in the naming of low frequency exception words which was predicted is not significant. The 7 ms. slowdown in the naming of high frequency exception words was not significant. The 7 ms. slowdown in the naming of high frequency consistent words was not significant. Finally, the 26 ms. slowdown in the naming of low frequency consistent words was marginally significant [$t(23) = -2.011, p = 0.06$].

Noun Task

In this condition, and this condition only, the predicted pattern of results appeared and was significant. The main effect of frequency was significant [$F(1,47)=63.145, p < 0.0001, MSE=4738$] in that high frequency words are pronounced faster than low frequency words (755 vs. 810 ms. respectively. The main effect of consistency was significant [$F(1,47)=28.724, p < 0.0001$, $MSE=3112$] in that consistent words were pronounced faster than exception words (767 vs. 798 ms. respectively). There was also a main effect of load [$F(1,47)=4.480, p < 0.05$] in that words were pronounced faster under a load of 1 item than a load of 5 items (772 vs. 793 ms. respectively). Most importantly, the predicted interaction of frequency, consistency, and load was significant [$F(1,47)=5.747, p < 0.05, MSE=3823$]; this interaction is graphed in Figure 19.

A series of four planned matched pairs t-tests were performed to look for significant changes in naming each of the word types across load; that is, the changes in each line appearing in Figure 19. Although the frequency by consistency by load interaction was significant, the predicted speedup in the naming of low frequency exception words is not significant here, but it does appear. The 39 ms. slowdown in the naming of high frequency exception words was significant, $t(47) = -2.335, p < 0.05$. The 26 ms. slowdown in the naming of high frequency consistent words was significant, $t(47) = -2.067, p < 0.05$. The 33 ms. slowdown in the naming of low frequency consistent words was significant, $t(47) = -2.563, p < 0.05$. Finally, the 15 ms. speedup in the naming of low frequency exception words was not significant, $t(47) = 1.072, p = 0.289$.

CVC Task

The predicted pattern of results fails to appear with the CVC task and there was not a significant interaction of frequency, consistency, and load. There was a significant main effect of frequency [$F(1,47) = 50.933, p < 0.0001$, MSE=3980] in that high frequency words were pronounced faster than low frequency words (741 vs. 787 ms. respectively). There was a significant main effect of consistency [$F(1,47) = 8.048, p < 0.01$, MSE=4179] in that consistent words were pronounced faster than exception words (755 vs. 773 ms. respectively). There was also a significant main effect of load [$F(1,47) = 9.247, p < 0.01$, MSE=7789] in that words are pronounced faster under a memory load of 1 item than under a memory load of 5 items (750 vs. 779 ms. respectively). Note that this 29 ms. load effect is just as large or larger than the 21 ms. effect observed in the noun task, where the predicted pattern of results was obtained. The only significant interaction in the CVC task naming latencies was the frequency by consistency interaction [$F(1,47) = 6.604, p < 0.05$, MSE=4639] in that the naming of exception words slowed across decreasing frequency (63 ms.) more than the naming of consistent words slowed across decreasing frequency (28 ms.).

A series of four planned matched pairs t-tests were performed to look for significant changes in naming each of the word types across load; that is, the changes in each line appearing in Figure 19. Notice that the predicted speedup in the naming of low frequency exception words does not appear here; just the opposite occurs -- a slowdown, though the slowdown is non-significant when tested individually. However, low frequency exception words are affected the least by load. The 34 ms. slowdown in the naming of high frequency exception words was significant, $t(47) = -2.246, p < 0.05$. The 34 ms. slowdown in the naming of high frequency consistent words was significant, $t(47) = -2.595, p < 0.01$. The 26 ms. slowdown in the naming of low frequency consistent words was not significant. Finally, the 16 ms. slowdown in the naming of low frequency exception words was not significant.

An additional test was done in which this 16 ms. slowdown in the naming latencies of low frequency exception words with CVC memory load was compared directly to the 15 ms. speedup observed with noun memory loads. This test was not significant, $t(47) = 1.561, p = 0.125$.

Picture Task

Again the predicted pattern of results fails to appear with the picture task. Here, as in the CVC task, instead of a speedup of low frequency exception words, there is a slowdown, just the opposite of what was predicted. There was a significant main effect of frequency [$F(1,46)=40.900, p < 0.0001, MSE=8152$] in that high frequency words are pronounced faster than low frequency words (725 vs. 785 ms. respectively). There was a significant main effect of consistency [$F(1,46)=23.516, p < 0.0001, MSE=2391$] in that consistent words are pronounced faster than exception words (743 vs. 767 ms. respectively). There was also a significant main effect of load [$F(1,46)=19.377, p < 0.0001, MSE=4410$] in that words were pronounced faster under a memory load of 1 item than under a memory load of 5 items (740 vs. 770 ms. respectively). This 30 ms. load effect is comparable to the 29 ms effect observed with CVC memory loads and the 21 ms. effect observed with noun memory loads. The interaction of frequency and consistency was significant [$F(1,46)=12.054, p < 0.001, MSE=2820$] in that the naming of exception words slowed across decreasing frequency (78 ms.) more than the naming of consistent words slowed across decreasing frequency (41 ms.). Although there was a significant interaction of frequency, consistency, and load [$F(1,46)=6.252, p < 0.05, MSE=3769$], the predicted speedup in the naming of low frequency exception words does not appear in Figure 19.

A series of four planned matched pairs t-tests were performed to look for significant changes in naming each of the word types across load; that is, the changes in each line appearing in Figure 19. The 12 ms. slowdown in the naming of high frequency exception words was not significant. The 48 ms. slowdown in the naming of high frequency consistent words was significant, $t(46) = -5.766, p < 0.0001$. The 17 ms. slowdown in the naming of low frequency consistent words was not significant, $t(46) = -1.523, p=0.135$. Finally, the 44 ms. slowdown in the naming of low frequency exception words was significant, $t(46) = -2.327, p < 0.05$.

Thus, while all word types were slowed to some extent by the picture memory load, some were slowed more than others. However, the pattern is not very systematic and the three factor interaction is not very strong ($p < .05$), suggesting that these differences may not deserve much attention.

As with the CVC memory loads, a specific comparison was made between the 39 ms. slowdown in the naming of low frequency exception words under load in the picture task and the 15 ms. speedup observed with noun memory loads. The comparison was significant, $t\ (47) = 2.338$, $p < 0.05$.

Discussion

This experiment was an exploration of word pronunciation, the purpose of which was to discover the nature of the underlying system using dual-task interference methodology. The dual-task paradigm was one in which subjects maintained a variety of interfering stimuli in memory while pronouncing words. This was expected to cause a dissociation in the naming of various types of words, which would be potentially indicative of the functional architecture of the visual word recognition system. Manipulating the type of interfering stimuli in the memory task was done to vary the level of the word recognition system at which interference was being generated: attentional interference from the picture task, attentional as well as assembled phonological-articulatory interference from the CVC task, and attentional as well as lexical or retrieved phonological-articulatory interference from the digit and noun tasks. Manipulating the size of the memory load was done to vary the amount of interference with word recognition.

The results and implications of this experiment will be discussed as follows: First, the nature of the findings will be reviewed with respect to what exactly the effects are of interference during naming at the various levels represented by each of the tasks. Second, characteristics this reveals about visual word recognition will be considered in light of other data in the field. Third, in the general discussion it will considered how the various models of visual word recognition which were reviewed in the introduction might handle this data. Fourth, conclusions will be drawn about the system. Finally, directions for future research which would test these conclusions will be suggested.

Just what exactly has been found?

Evidence was sought for a multiple route model of the word recognition process, such as the Parallel Coding Systems (Carr and Pollatsek, 1985) and various dual-route models (Paap and Noel, 1991; Paap et al. 1987; Coltheart, 1978). The pattern of naming latencies which Paap and Noel observed in a dual task experiment using memory for digits while naming words was an interaction between word frequency, word consistency, and memory load. This interaction resulted from a speedup in the naming of low frequency exception words under high memory load as compared to low memory load, and a slowdown in naming under load for high frequency consistent words, low frequency consistent words, and low frequency exception words. According to Paap and Noel, this speedup in naming was due to a release from competition caused by the simultaneous production of two conflicting answers by the memory and OPC routes to word pronunciation; a situation which arises in the course of pronouncing low frequency exception words. According to Paap and Noel, the release from competition between the two routes occurred because the memory load of the interfering task was stealing attentional capacity which the OPC route required to operate. That is, handicapping one horse in the horserace significantly reduced competition between the two routes, in turn causing a speedup in the naming of words which suffer from competition.

The current experiment questioned the attentional explanation which Paap and Noel offered. Specifically, was it attention demand which was interfering with the operation of the OPC route or was the interference due to something more like crosstalk or outcome interference -- either competition among sub-lexical components involved in both the maintenance of the memory load and pronunciation of the word name, or competition among lexical representations involved in both the memory load and the naming task. To answer this question interference was generated at various levels of the word recognition system by the four different tasks, looking for the interaction of frequency, consistency, and load within each of the tasks as an indication of the release from competition effect. If this pattern of results emerged with some types of interference and not others, the locus of the slowdown in the OPC route could be pinpointed.

This key pattern of results, the interaction of frequency, consistency, and load, was not significant in the overall analysis. The interaction of frequency, consistency, load, and task was significant in the overall analysis, confirming the possibility that varying the type of interfering stimuli would affect the pattern of results observed by Paap and Noel with digit stimuli. Thus, it makes sense to discuss the effects of each task independently because some tasks cause the effect while other tasks do not. Because stimuli did not enter into this interaction, the differences between the two sets of naming stimuli will be discussed separately from the effect of the four tasks.

Attentional Interference: The Picture Task

Paap and Noel suggested that the OPC route makes use of limited capacity attention while the memory route is automatic. The picture task in the current experiment was intended as a relatively pure manipulation of attention demand, mostly free of the systematic phonological and articulatory processes present in the other three conditions in which the stimuli were readily nameable. Past short term memory research indicates the names constitute the codes used to support memory maintenance. Some subjects did report having named the pictures, but compared to the other conditions the articulatory component of remembering pictures is arguably weak. At the very least, the names subjects gave the pictures, and consequently the articulation associated with these names, were definitely not consistent among the subjects. The articulation associated with memory for nonsense syllables, digits, and nouns was very consistent across subjects. In the calibration experiment, increasing memory load in the picture task caused a significant slowdown in tone latencies, which provides support for the claim that increasing load in the picture task increases attention demand.

If attention demand alone was the cause of the Paap and Noel results, that is, the stealing of attention which the OPC route requires to operate, then their pattern would have appeared in the picture task; clearly it did not. Instead, attention demand slowed down the entire word recognition process, as evident in the main effect of load on naming latencies. Load in the picture task did not interact in a systematic way with frequency or consistency, which suggests that if there are two routes to word pronunciation, they do not differ in their use of the kind of attention which was manipulated in the picture task.

Interference From Assembled Phonology and Articulation: The CVC Task

The nonsense syllables which were used as memory load stimuli in the CVC condition were intended as a manipulation of phonological-articulatory interference as well as attention demand. To avoid a semantic component to the CVC task, nonsense syllables were chosen which were rated as being low in meaningfulness in the Underwood and Schulz (1960) norms. To avoid letter matching strategies, thus encouraging subjects to remember the CVC's by pronouncing them, many first letters were repeated in the CVC memory set. The interference which was generated by the CVC's can be regarded as occurring at a sub-lexical level. The reason that interference in the CVC condition is said to be at the sub-lexical level is that CVC's presumably do not have lexical representations in memory but do consist of orthographically legal combinations of letters that map onto phonologically legal combinations of sounds and articulatory gestures.

Of the three tasks which were calibrated, the CVC task represents a moderate attention demand and the heaviest sublexical or assembled phonological-articulatory demands. This task is certainly sufficient as an imposition of heavy phonological-articulatory demands for the purposes of the current experiment.

If sublexical or assembled phonological-articulatory interference were the cause of the Paap and Noel results, their pattern would have occurred with the CVC task; clearly it did not occur here either. Instead, there was a main effect of memory load in the CVC task - increasing load slowed naming of all four types of words. Load in this condition did not interact with anything, although the t-tests reveal that the slowdown in the naming of high frequency words with increasing load is significant while the slowdown in the naming of low frequency words with increasing load is not significant. Whatever the cause of this difference, the lack of a significant interaction of frequency and load make interpretation of this difference at best problematic and at worst unjustified.

The main effect of load in the CVC condition suggests that interference at sub-lexical levels of the word recognition system cause an overall slowdown in naming, regardless of word type. Because consistency did not interact with load in the CVC condition, it suggests that this type of phonological-articulatory interference acts similarly on the naming of consistent and exception words. This result does not speak to the independence of the two routes in that the lack of an interaction between load and consistency does not necessarily mean that consistent and exception words are handled by the same mechanism; just that they

both suffer a similar fate when interference is at the sub-lexical level. It is equally possible that there could be either a shared sub-lexical representation in the memory and OPC routes or that there could be independent but identical representations at the sub-lexical representation. Alternatively, since the effects of the CVC memory load are quite similar to those of the picture memory load, it may be the attention demands of the CVC load that are operative - CVC memory loads may not cause crosstalk interference of any kind in the word recognition system. While these are interesting questions, the answers to which are central to dual route theories, they cannot be answered based upon the results of this experiment.

Retrieved or Lexical Phonological/Articulatory Interference I: The Digit Task

This condition was a replication of the Paap and Noel experiment. The calibration experiment demonstrated that there is an attention demand to remembering digits in that there was a significant slowdown in tone latency with an increase in digit load. Attention demand in this task is probably the smallest - in the calibration experiments this task produced the smallest impact on tone latency and in the naming experiment it produced no significant effect on naming latency. Digits also are represented in lexical memory, and presumably have representations at a semantic level as well. Thus, it can be said that the digit memory task may cause interference at semantic and lexical levels as well as imposing a small attention demand.

If the Paap and Noel results are replicable, and due to interference at the various sites represented in the digit memory task, their pattern of results would appear in this condition. Their pattern of results did appear here but was not significant in that the interaction of frequency, consistency, and load was not significant. The planned t-tests revealed that increasing load did cause a non-significant speedup in naming latencies of low frequency exception words and non-significant slowdowns in naming latencies of all other types of words. This is clearly the predicted pattern, but the effects of the digit load are very small. The theoretical implications of this kind of interference will be discussed along with those from the noun task.

Retrieved or Lexical Phonological/Articulatory Interference II: The Noun Task

In this condition, the stimuli which interfered with naming were high frequency nouns. This condition was added to the original experiment when it became apparent based upon preliminary data analysis that the presence of high frequency words in the memory load might be necessary to obtain the release from competition effect. The noun stimuli were intended to cause interference at the lexical and semantic levels of the system. The attention demand of remembering these stimuli is unknown as they were not used in the calibration experiments. Based upon the results of the other three calibration experiments, it would be a reasonable assumption that there would be evidence for an attentional component to this task as well, if it were tested, and this type of load did produce a significant main effect on naming latency in the naming task. Nevertheless, the

important aspect of these stimuli in comparison to the CVC and picture stimuli is the interference which they can generate at the lexical and semantic levels.

If the Paap and Noel results are due to the presence of high frequency words in the memory load, their pattern of results should appear in this condition; it did. The interaction of frequency, consistency, and load observed by Paap and Noel appeared here and was significant. The planned t-tests investigating this interaction revealed that the speedup in the naming of low frequency exception words failed to reach significance but the slowdowns in the naming of the other three types of words were all significant.

Differences between the Noun and Digit Tasks

These two lexical interference conditions demonstrate that the Paap and Noel results indeed can be replicated, at least with respect to overall pattern. The pattern of their results indicating the release from competition effect was present but not significant in the digit condition and was present and significant in the noun condition. Although the release from competition effect was not present in the digit condition, a comparison of size of the speedup effect in the naming of low frequency exception words proved this effect in the noun and digit conditions was virtually identical -- 15 ms and 14 ms respectively. Therefore the difference in results between the two tasks lay in the size of the slowdowns in naming the other three types of words: high frequency consistent words, high frequency exception words, and low frequency consistent words.

The difference in the load effect when digits vs. nouns are the memory stimuli could be due to differences in their lexical/semantic representations. Specifically, while both digits and nouns do have semantic and lexical level representations, it may be the case that the noun representations are more easily confused with the representations of the naming stimuli than the digit representations.

This distinction between noun and digit interference makes sense if one considers the memory stimuli as serving a role in performance similar to the role of inhibitory semantic primes. Inhibitory semantic primes are indisputably different than memory load stimuli, but it is possible that the effects of the two are similar. Inhibitory semantic priming is the slowed recognition of a word due to confusion in the system. Posner and Snyder (1975) explain this in terms of a focal attention mechanism which is mislead by a high validity prime, such that attention is in effect enhancing the activation of the wrong logogens in memory. This slows readout from the correct logogen.

In the case of interference at the logogen level by a memory load of five nouns, readout from the correct logogen could be slowed because of increased activity in other logogens. Both the interference effect of a memory load and the effect of an inhibitory semantic prime have the same consequence: slowed recognition of a word because it takes longer to find the logogen that is turned on the most.

The difference between the digit and noun conditions may be due to higher confuseability of categories of words which are semantically similar. Neely, Keefe, and Ross (1989) as well as Keefe and Neely (1990) found that in lexical decision tasks there is a smaller semantic inhibition effect at long SOA's for unrelated categories than for related categories. This demonstrates that in a lexical decision task words which are semantically related in memory interfere with each other more than words that are semantically unrelated. If this difference extends to naming tasks, and if semantic inhibition and interference both slow naming, it could be the case that the memory load generates more interference in the noun task than in the digit task because the nouns are closer in semantic relatedness to the naming stimuli than the digits are. While this explanation of a semantic relatedness effect in naming is plausible, it remains to be tested empirically.

Chapter IV
General Discussion

Paap and Noel observed the speeded naming of low frequency exception words under load while the naming of the other three types of words were slowed. They proposed that the cause of this interaction was an attentional shortage interfering with the operation of the rule governed OPC route, avoiding a conflict in the system, the release from competition between two routes to naming a word. The point of this experiment was to determine if this interaction was due to a simple effect of attention demand, as they proposed, a simple effect of phonological-articulatory interference, a simple effect of lexical interference, or some combination of these effects.

Explaining Attentional Interference

The attention required to maintain a picture load does not cause Paap and Noel's pattern of results. This kind of attention demand appears to slow input to the whole system. Stealing this kind of attention does not differentially slow the naming of words based upon frequency or consistency.

Theoretical Implications

With regard to a dual route theory, based on the results of this condition alone, it would appear that stealing this kind of attention does not harm the OPC route more than the lexical route. This could mean one of four things: (1) The operation of the OPC route does not require this kind of central capacity. Given the result of the second Paap and Noel (1991) experiment, this is not a likely explanation. (2) Both the OPC and lexical routes employ this kind of attention to a similar extent. This is a viable possibility. (3) The kind of attention that a picture task employs is not the central capacity attention which the OPC route requires to operate. This third possibility is not very likely considering both the results of the second Paap and Noel (1991) experiment and the calibration experiment in this paper. Paap and Noel demonstrated that word recognition when the OPC route is operating is attention demanding as measured by tone detection. Similarly, the calibration experiment demonstrated that maintaining a memory load of picture stimuli is attention demanding as measured by a tone detection task. Tone detection tasks are considered to be a fair measure of available central capacity. Therefore, both word naming with the OPC route and picture memory seem to engage central capacity. (4) The kind of attentional interference generated by the picture task could act elsewhere in the system, perhaps early on. Whether the second or fourth explanation are the cause of the effect of attention on naming in this experiment depends on what kind of attention the picture task is engaging.

What Attention System is Being Engaged?

The question remains as to just what attentional system the picture task is occupying and what the role is of this attentional system in reading. Posner and Peterson (1990) distinguish three attentional systems: the anterior attention system, the posterior attention system, and the vigilance system. According to Posner and Petersen (1990), when subjects are required to process visual imagery, parietal areas of the cortex are active, areas which are part of the posterior attention system.

The posterior attention system areas responsible for the integration of features in space and the processing of images are the same areas which Mozer and Behrmann (1991) claim are involved in visual word recognition. Damage to these areas causes deficits in the processing of mental images, spatial neglect (Bisiach, Luzatti and Perani, 1979). Hillis and Caramazza (1990) report that patients who exhibit spatial neglect due to brain injuries also have acquired dyslexia in that they neglect portions of words. Sieroff and Posner (1988; Cited in Mozer and Behrmann, 1990) find that when attention is engaged elsewhere, normal subjects neglect portions of nonwords presented in the periphery but not portions of words in the periphery. All this evidence suggests that attention plays an early role in getting word information into the reading system. When attention is occupied elsewhere, top down information from semantics can compensate for the lack of attention.

Theoretical Implications

Many models of word recognition can potentially explain this facet of the results but only Mozer's BLIRNET explicitly predicts this. There is no defined use of attention at a global level in dual route models (Paap and Noel, 1991; Coltheart et al. 1979; Paap et al, 1987) or the in Parallel Coding Systems Model (Carr and Pollatsek, 1985). The dual route model of Paap and Noel (1991) uses attention in the operation of the OPC route, not in the overall operation of the system. The second experiment in their 1991 paper demonstrated that when the balance of a word list encouraged the use of the OPC route, tone latencies were longer than when the balance of a word list encouraged the use of the memory route. They interpreted these results as support for the attention demands of the OPC route. Since these models as they are explicitly stated use attention in the OPC route and not in the memory route, they do not explain the overall slowdown in naming latencies with increased attention demand.

A "molasses" approach in a PDP model (i.e. Seidenberg and McClelland, 1990) -- slower flow of activation everywhere under attention demand -- would be compatible with the overall slowdown in naming latencies with increased attention demand; but this is not explicitly stated in such models. The same would be true of interactive activation models (Rumelhart and McClelland, 1981) and logogen models (Morton, 1969; Morton, 1979).

Lexical search models (Forster, 1976; Taft and Forster, 1975, 1976) do not address the issue of attention demands either. Extending these models to incorporate attention involves morphemic decomposition, an issue which is separate from frequency and consistency. The issue of attention demands is also not addressed by single-route phonological mediation models (Lukatela and Turvey, in press).

Verification models of word recognition (Becker, 1976; Herdman and Dobbs, 1989; Paap and Ogden, 1981; Kellas, Ferraro, and Simpson, 1988; Herdman, in press 1991) do use attention at the global level to compare the representation of the word being processed with entries from the lexicon. However, verification models predict that attention demand will interact with word frequency such that the recognition of high frequency words requires less attention than the recognition of low frequency words. In the current experiment frequency and attention load did not interact in the picture task; all words suffered a comparable slowdown in the face of an attention shortage. Verification models would predict that the naming of low frequency words would suffer a more severe slowdown than the naming of high frequency words, a frequency by load interaction.

One model which does use attention at a global level is Mozer's BLIRNET (Mozer, 1987; Mozer and Behrmann, 1991). Mozer points out that attention acts in many ways in word recognition. These include but are not limited to: the control the order of processing on a page, restricting input to the system to prevent crosstalk, and binding letter identities to locations in space. To explain the picture task in the current experiment, a function of attention is needed which is global and which operates even in single word reading studies. The relevant facet of attention in his model is its role in restricting the information which is transmitted from early visual feature analysis to the actual word recognition system. That is, spatial attention serves to gate the flow of information from visual areas to areas dedicated to reading. In terms of the Posner and Petersen (1990) taxonomy of attention, spatial attention is a function of the posterior attention system. Thus, Mozer's model is consistent both with the neuropsychological data and the overall slowdown in naming latency with increasing load in the picture task.

Explaining Assembled Phonological-Articulatory Interference

The Paap and Noel pattern of results is not generated by maintaining nonsense syllables in memory in the CVC task. This kind of interference slows everything. In terms of a dual route theory, all that can be said here is that this kind of interference affects naming of all kinds of words. This could mean that both routes to pronunciation are equally affected.

Distinctions between interference caused by this task and the picture task should be made with caution. It was demonstrated in the second calibration experiment that there was a significant attention demand present in both the picture and CVC conditions. However, the version of the CVC condition run used different nonsense syllables than in the calibrated version. This nonsense syllable list was constructed to make the task a little more difficult in that it was intended to foil letter matching strategies. If one concludes from the calibration experiment data that both tasks represent a significant attention demand effect, the addition of assembled articulatory-phonological interference with the CVC condition still slows the naming of all types of words comparably.

Thus, one can say that the interaction which Paap and Noel reported is not due to attention alone, and is not due to attention plus assembled phonological-articulatory interference. Because the CVC task represents a significant attention demand as well as assembled phonological-articulatory interference, the effect of phonological-articulatory kind of interference without the added attentional interference remains unknown.

Theoretical Implications

This aspect of results, the lack of the release from competition effect when CVC's are the memory load, is a problem for both the dual-route models and the Parallel Coding Systems model. The problem here is twofold: First, the CVC condition represents an attention demånd which should interfere with the operation of the OPC route, as in the picture task. Second, the CVC task generates articulatory, assembled-phonological interference, which should particularly affect the OPC route, the business of which is to assemble phonology. If the OPC route is a rule-governed system for sounding words out, then the CVC's should have placed a considerable burden on it, slowing it down, and causing the release from competition effect. Considered along with the results of the picture task, it can be said that whatever is causing the interaction of frequency, consistency, and load, it is neither a simple effect of attention nor the combined effects of attention and articulatory, assembled-phonological interference.

This result does not necessarily present a present for logogen models, and the interactive activation model in that the CVC task could be generating interference at a level of representation below the word level (even at the letter level), causing the overall slowdown. It is hard to say how the PDP model would handle this result because the nature of the interface between the distributed representation and working memory is unclear in the implemented model. Specifically, this is not a problem for the PDP model if the addition of noise in the hidden units causes an overall slowdown but it is a problem if the addition of noise in the hidden units would cause mispronunciations. Verification models also do not specify how concurrently active nonsense in working memory would affect the naming of words. Attentional predictions follow easily from the verification models but predictions regarding this kind of interference does not. Lexical search models also make no clear predictions regarding this kind of interference.

Explaining the Digit and Noun Conditions

The evidence which was sought for the dual route models and the Parallel Coding Systems model, a significant interaction of frequency, consistency, and load in the digit condition, was not present. This would have been evidence for the release from competition between the two routes to naming a word. Instead, in the digit and noun conditions, the predicted pattern of results appeared and reached significance only in the noun condition (Although the predicted absolute speedup in the naming of low frequency exception words under high memory load compared to low memory load did not reach significance in either task.).

While the appearance of this pattern of results in the digit condition does not present a problem for the dual-route models and the Parallel Coding Systems model, the lack of significance in this condition, and the appearance and significance of the pattern in the noun condition does present a problem. Specifically, these models do not predict that a memory load of high frequency words, as was the case in the noun condition, should interfere with the generation of assembled phonology. They predict that the pattern will result from the stealing of attention, which is required by the rule governed assembly process operating within the OPC route.

Thus, the interaction of frequency, consistency, and load in the Paap and Noel experiment was believed to be the result of two occurrences in a dual route model (1) shutting down of the OPC route and (2) a general slowdown in naming. The fact that low frequency exception words were much slower than other words due to competition made the release from competition effect greater than the effect of the overall slowdown, causing the frequency by consistency by load interaction.

Instead of attention demand causing the release from competition effect, the presence of high frequency words in the memory load, as seen in the digit and noun conditions, causes the interaction of frequency, consistency, and load. This evidence fails to support the notion that the OPC route consists of a set of rules which require attention for their operation. The question which was asked at the beginning of this endeavor was in regard to the locus within the rule governed OPC route at which the interference was having its effect. A more appropriate question would have been, does the OPC route consist of rules?

Rosson points out that "the fact that readers easily generate pronunciations for completely novel words has often been taken as prima facie evidence for the existence and use of pronunciation rules" (1985, p. 90). She, and other analogy theorists (i.e. Glushko, 1979) argue that pronunciation of novel and known words can be generated by analogy to known words, rather than by the application of rules. In Glushko's (1979) activation-synthesis model of word pronunciation, the pronunciation of a word is the result of a synthesis of candidates activated by a visual word form.

Explanation of the interaction of frequency, consistency, load, and task

The key result to be explained here is not the interaction of frequency, consistency, and load, which appears in the noun task, but the interaction of frequency, consistency, load, and task; that is, the significance of the frequency, consistency, load interaction only in one of the four tasks. The question is where is this interference acting to produce this pattern of results? What does this say

about the architecture of the system? None of the models reviewed in this paper, as they now stand, are capable of explaining that interaction. The best bet for explaining the interaction of frequency, consistency, and load is a dual route model. Explaining the four way interaction with task requires some modification of the dual route models.

If one were to modify the dual route and Parallel Coding Systems models, keeping the dual route horserace architecture but replacing the rule governed OPC route with an analogy based process, such an explanation is possible. The interference which is generated by the digit and noun tasks could simply be due to the memory load interfering with the synthesis process in an activation synthesis route, which operates like Glushko's (1979) model.

This solution retains the horserace setup, in which direct access to memory from the visual form begins simultaneously with a retrieved phonology process, in which the activation-synthesis process (ASP) is used to generate the pronunciation of the word by analogy to known words. The process that finishes first, wins. In the case of high frequency words, direct access is faster than ASP. With low frequency words, direct access and ASP can tie. With consistent words, the pronunciation generated by ASP is often correct, as these words sound like their neighbors, from which the assembled pronunciation was synthesized. With inconsistent words, the pronunciation generated by ASP is often incorrect, as these words do not sound like their neighbors, from which the assembled pronunciation was synthesized. When there is a tie between the two routes, time is required to make a decision between the two answers. Memory is given precedence in these cases, but time is required to make the decision nonetheless.

Low frequency exception words are pronounced slowest, because there is a tie with conflicting answers from direct access and ASP. High frequency words could be spared this cost because their representations are directly activated by the visual form, before ASP has a chance to operate. The presence of a memory load slows naming overall, as seen in all conditions in the naming experiment. However, when this memory load is a set of words the ASP is interfered with, because the memory load gets confused with the candidate set which is synthesized to form the pronunciation. This eliminates the time consuming tie between the direct access and ASP routes, which had made the naming of LFE words slowest overall, a release from competition.

This solution, one in which the pronunciation of words and nonwords is handled by the same mechanism, is not only consistent with the evidence which supports the analogy models of word pronunciation (Glushko, 1979; Rosson, 1983, 1985), but is also in agreement with recent data in cognitive neuropsychology. Petersen, Fox, Snyder, and Raichle (1990) find that in PET studies of regional cerebral bloodflow during reading, the same areas of cortex were activated by the reading of real words as well as by the reading of pseudowords which follow the rules of English. Nonsense strings of letters which did not follow the rules of English morphology did not activate these areas. This supports the notion that real words and pseudowords are handled by the same mechanism.

Chapter V
Conclusion - A Modified Multiple Route Approach

The results of these experiments clearly support a multiple route model of word pronunciation, but they do not support an existing model. The multiple route approaches to word recognition and pronunciation reviewed in this paper all involve a direct access route and an orthographic to phonological conversion (OPC) route. The OPC route in these models is a rule governed assembly of phonology. Paap and Noel argue that the use these rules requires attention, and their existence is supported by the interaction of attention demand with frequency and consistency in a naming task. However, manipulation of attention demand alone failed to cause this interaction. Since a rule governed OPC route would also be responsible for the pronunciation and maintenance in memory of nonsense syllables, these should also have caused this interaction if such rules exist. A memory load of nonsense syllables did not cause this interaction. Instead, this interaction was caused by a memory load of items which are words.

An activation-synthesis process (ASP) is the simplest explanation for why the existence of words in working memory would interfere with the generation of assembled phonology. Such a process is proposed by Glushko (1979). However, Glushko's model is a single route approach, one which does not allow direct access to memory representations from the visual form. Therefore, Glushko's model cannot explain these results. A multiple route approach, such as the Parallel Coding Systems model (Carr and Pollatsek, 1985) and dual route theories (Coltheart, 1979; Paap et al. 1987; Paap and Noel, 1991) can explain these results if the rule governed orthographic to phonological conversion (OPC) process is replaced with an activation-synthesis process (ASP). In such a model the two routes, direct access and ASP, operate in a horserace fashion, with a decision required in case of a tie. There is the usually fast direct horse and the slow ASP horse. The slow ASP horse does not always give the right answer, and in the case of a tie with exception words, extra time is required. To paraphrase Paap and Noel, dual route theories are still a good horserace, but one of the horses is a horse of a different color.

APPENDICES

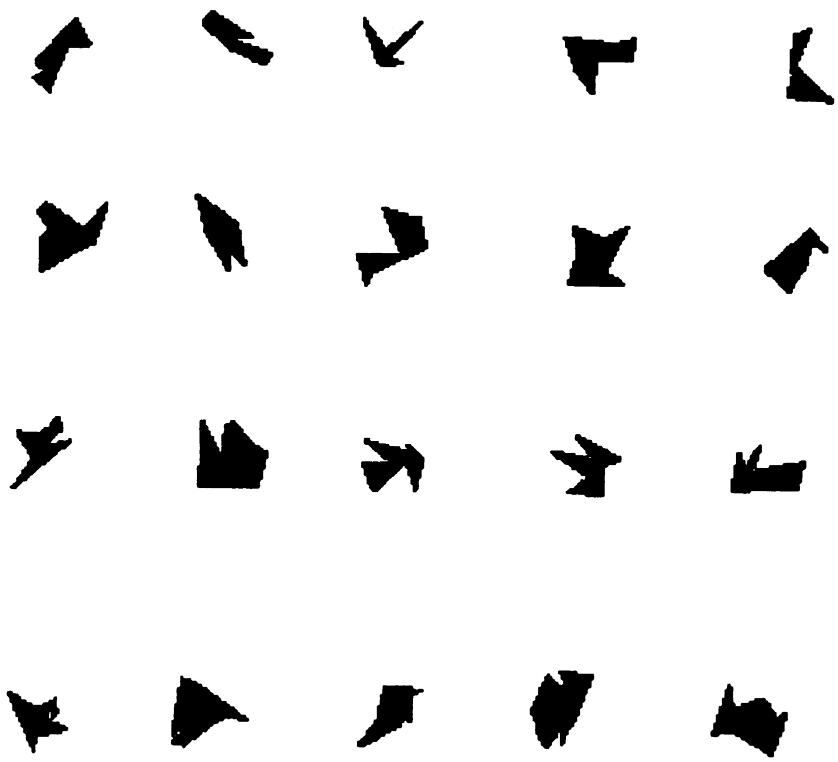
Appendix A

Calibration Experiment #1
Nonsense Syllables

BEM
BIV
BUP
CUX
DEJ
DEZ
FAP
GAK
GEB
HIF
JEG
KAX
MEF
NID
RIX
SUZ
TOV
TOZ
VEP
WIB

Appendix B

Calibration Experiment 1
Attneave Figures



Appendix C

Subject Instructions

Calibration Experiment

This experiment is a test of your memory for a series of digits. A display of one, three, four, or five digits will appear on the computer screen. This 'study set' will remain on the screen for a brief period of time. Your task is to remember all of these items. After a few seconds, during which a blank screen will be displayed, a single digit will appear on the screen. If it was in the study set, press the "." key with your right index finger. If the item was not in the study set, press the "/" key with your right middle finger. You may take as long as you need to respond. Please try to be as accurate as you can. Each trial will begin with the presentation of a visual warning signal, a "+ which will appear in the center of the screen. It is your cue to "get ready, here comes another study set."

Sometime during the delay between the presentation of the items you are to remember and the test item a tone will sound. As soon as you hear this tone, please press the "Z" key with your left index finger. It is important that you respond as soon as possible after you hear the tone but remember that we are most interested in your performance on the memory test. There will be 16 practice trials before the 80 actual trials so that you can become accostomed to using the keyboard for your responses.

Appendix D

Naming Task Stimuli

Paap & Noel Stimuli

Low Frequency		High Frequency	
Exception	Consistent	Exception	Consistent
BURY	BUDS	BEEN	BEST
CASTE	CANES	BOTH	BOOK
COMB	COIL	COME	CAME
CROW	CURL	DONE	DARK
GLOVE	GRADE	DOOR	DEEP
LURE	LUMP	FOOT	FLAT
LUTE	LODE	GIVE	GAME
PEAR	PEER	GOOD	GAIN
POUR	POPS	HAVE	HIGH
RUSE	RUMP	MOST	MORE
SEW	SOCK	MOVE	MISS
SANS	SAGE	SAID	SAME
SUES	SUCK	SAYS	SEEM
SOWN	SOBS	SURE	SOON
WAND	WADE	TOUCH	TRAIN
WARN	WEED	WANT	WALL
WARP	WICK	WARM	WAGE
WASP	WELD	WERE	WELL
WOOL	WOKE	WORD	WEST
WORM	WINK	WORK	WEEK

Appendix D cont'd

Naming Stimuli
Taraban & McClleland Stimuli

High Frequency		Low Frequency	
Exception	Consistent	Exception	Consistent
ARE	OUT	BOWL	BUS
BOTH	BIG	BROAD	BROKE
BREAK	BEST	BUSH	BEAM
CHOOSE	CLASS	DEAF	DEED
COME	CAME	DOLL	DOTS
DO	DID	FLOOD	FLOAT
DOES	TELL	GROSS	GRAPE
DONE	DARK	LOSE	LUNCH
FOOT	FACT	PEAR	PEEL
GIVE	GOT	PHASE	FADE
GREAT	GROUP	PINT	PITCH
HAVE	HIM	PLOW	PUMP
MOVE	MAIN	ROUSE	RIPE
PUT	PLACE	SEW	SLIP
PULL	PAGE	SHOE	SANK
SAID	SEE	SPOOK	SLAM
SAYS	STOP	SWAMP	STUNT
SHALL	SOON	SWARM	SWORE
WANT	WHICH	TOUCH	TRUNK
WATCH	WEEK	WAD	WIT
WERE	WITH	WAND	WELD
WHAT	WHEN	WASH	WAX
WORD	WRITE	WOOL	WING
WORK	WILL	WORM	WAKE

Appendix E

Subject Instructions

Naming Experiment
(Cover Name -- Memory Span Experiment)

This experiment is a test of your memory for a series of nonsense syllables. A display of one, four, five, or six syllables will appear on the computer screen. This 'study set' will remain on the screen for a brief period of time. Your task is to remember all of these items. After a few seconds, during which a blank screen will be displayed, a single syllable will appear on the screen. If it was in the study set, press the "." key with your right index finger. If the item was not in the study set, press the "/" key with your right middle finger. You may take as long as you need to respond. Please try to be as accurate as you can.

Sometime during the delay between the presentation of the items you are to remember and the test item a tone will sound. As soon as you hear this tone, please press the "Z" key with your left index finger. It is important that you respond as soon as possible after you hear the tone but remember that we are most interested in your performance on the memory test. There will be 16 practice trials before the 80 actual trials so that you can become accostomed to using the keyboard for your responses.

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