Concurrent processing of visual and auditory information: An assessment of parallel versus sequential processing models.

Greg Evans
B. Sc (Hons) Adelaide.

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Department of psychology
University of Adelaide
South Australia

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Summary

The introduction of high speed processing technology in the 1940s emphasized man's limited ability to process more than one source of information at a time. As process and control technology improved, it became increasingly evident that the 'weak link' in a man-machine system was the limitations of the operator. To utilize this technology effectively, it is essential to understand not only factors that limit the performance of the human operator, but also to develop a reliable model of the human information processing mechanism which is capable of predicting complex behaviour.

Traditionally, the study of cognition has centred around the operator's ability to deal with two or more simple tasks at the same time. This experimental technique, generally known as the dual-task paradigm, is assumed to mimic the type of cognitive functioning required for skilled performance. However, results obtained from a wide range of studies using different variants of the dual-task method have not always provided a consistent interpretation of human cognitive abilities. In some situations, two seemingly complex tasks can apparently be easily performed either singly or paired together, without adverse effects. An example of this was reported in a study using a piano playing, sight reading primary task combined with a visual memory secondary task (Allport, Antonis & Reynolds, 1972). Subjects involved in this study achieved approximately the same memory recognition scores, regardless of whether they were required to play from a musical score while attending to a visual display, or if they attended to the visual display only. On the other hand, studies which involve two quite simple tasks often result in significantly worse performance when the two task are combined than when they are attempted alone. In situations where the performance of one task is adversely affected by the concurrent performance of a second task, interference is said to have occurred.

The nature and underlying cause of interference is one of the fundamental issues that an information processing model must be capable of explaining. Basically, two distinct types of theoretical models have been proposed. The first type (known as structural models) attributes interference to a particular processing stage or operation that can deal with only one signal at a time. If this stage is occupied with one signal, a subsequent signal must be 'held in store' until the stage is free to accept it. Thus, this stage is assumed to cause a 'structural bottleneck'. On the other hand, advocates of the second type (known as capacity models) argue that there is a general limit to the amount of

processing capacity available for any cognitive function. Up to this limit, one or more signals may be processed without interference. However, once the limit of available processing capacity is reached, further signals can only be processed if capacity is diverted from an existing operation. Thus, interference arises when two tasks compete for a share of the limited capacity. Although both structural and capacity models were originally proposed in the 1950s, it is still unclear whether either of these types of models can adequately account for the diverse results obtained from dual-task studies, or indeed if either model provides a reasonable description of skilled performance.

This thesis is concerned with the operator's performance when confronted with two concurrent tasks; in particular, whether both tasks can be processed at the same time; or if one is processed (either partially or completely) before processing of the second begins. Given an established level of single task performance, a simple model derived from the theory of perceptual independence has been applied to define the outcomes expected, depending on whether data were processed in parallel or in sequence. The procedure used to test dual-task performance involved a visual inspection time (IT) task and an auditory tone discrimination (ATD) task. Before commencing the main study, the backward masking procedure used to control the exposure of the visual target stimulus was redesigned to overcome problems associated with apparent movement cues. Using this masking procedure, a level of single-task performance for both IT and ATD at 85% accuracy was established. Dual-task performance of 14 subjects was subsequently assessed. At the completion of the dual-task subjects answered a short questionnaire about the way in which they performed the two tasks, in both the single and dual-task conditions. Results indicated some support for both parallel and sequential processing models. Nevertheless, the responses to the questionnaire showed that subjects were unanimous in their opinions that they had performed the dual-task by adopting a time-sharing strategy; in other words, by performing one task first before recovering information about the second task from memory to complete the dual-task. Analysis of the proportion of correct responses for each task highlighted a problem with the ATD task that may have encouraged subjects to use a time-sharing strategy. Performance of the auditory task was significantly better than predicted from single-task performance. To account for these data, two possible explanations were proposed; either the auditory backward recognition masking stimulus was ineffective; or alternatively, the task involved an extended period of learning and as a result, the single task performance level initially obtained at 85% accuracy was erroneous.

To overcome difficulties observed during dual-task performance, the procedure used for the visual and auditory discrimination tasks were revised to include a 'blank interval' of variable duration between the offset of the target stimulus and the onset of the mask. This procedure was intended to allow better control of the amount of information available from the target stimulus, thereby minimizing the use of a time-sharing strategy. The revised procedure for the visual task used a cue located centrally between the long and short target lines, the presentation of a target stimulus (for a fixed period of time), a 'blank interval' of variable duration and finally a flash mask. A similar procedure was used for the auditory task. Additionally, the auditory procedure was modified by the inclusion of a 'white noise' component to improve the effectiveness of the backward masking stimulus. The reliability and consistency of revised procedures for both the visual and auditory tasks were evaluated in a series of short experiments. The accuracy of estimates of visual and auditory single-task discriminations obtained using a maximum likelihood estimation procedure (Wetherill & Levitt, 1965) were compared using SPSS-X Probit Analysis. The results obtained from these procedures showed a significant discrepancy between the magnitude of the two estimates of sensory discrimination. However, it was impossible to determine from the results of this study which of the two procedures provided the most accurate estimate.

The results of dual-task performance measured in a final experiment using the revised procedures were similar to the results previously obtained; but, in this study, subjects performed the visual task very accurately, rather than the auditory task. The results of the questionnaire also indicated that performance was essentially on a time-sharing basis. It was argued that to overcome limitations in the processing mechanism, the operator typically adopts some form of strategy when asked to performance complex tasks. Further, subjects apparently become more reliant on 'subtle cues' associated with the target, particularly as they become more skilled at performing a task. Thus, responses to concurrent tasks may be based on performance criteria different than those associated with single-tasks. Nevertheless, it was clear that problems associated with backward masking of auditory signals make it particularly difficult to determine exactly how concurrent tasks are processed.

The implications of the results of this study were discussed in terms of our understanding of the human information processing mechanism, and in particular, the nature of the decision mechanism. Some broader implications concerning the way in which different environmental input is processed and its possible impact on the decision mechanism were also considered. Several limitations resulting primarily from uncontrolled variables, such as the use of strategies and practice effects were examined. The effects of a number of other variables, such as changes in the level of attention were also reviewed. Finally, after considering the pitfalls of the present study, an outline was provided for possible directions for future research on the nature of concurrent performance.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University or other tertiary institution and, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text.

I give consent to this copy of my thesis, when deposited in the University library, being available for loan and photocopying.

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Chapter 1

Information processing theory

1.1 Introduction

A number of basic questions confronting researchers in the field of information processing concern the human operator's ability to deal with two (or more) simultaneous events. Does the operator, faced with two complex signals process them concurrently; or must each signal, in turn, pass through a 'limited capacity' mechanism before processing can be completed? And if there is a limited capacity, is it general to all sensory processing and allocated to each signal as required; or does each sensory modality have its own specific capacity which is allocated for processing signals in that mode only?

Answers to these questions are important not only to our theoretical understanding of human behaviour, but they are particularly relevant to humankind's social and economic well being. In an industrial environment, the skill of the operator is frequently crucial to the success of an industrial or manufacturing process. For example, our technical understanding of information processing behaviour has a significant impact on the way we train people to perform complex tasks. It also has an effect on the design of the man-machine interface and, therefore, on the role of the operator in modern society. Consequently, the way we design and construct our industrial environment and how we utilize human resources in this environment is determined to a large extent by our theoretical understanding of information processing capabilities.

Although the development and use of sophisticated high speed processing and control equipment in the manufacturing sector has improved productivity and efficiency dramatically, it has also created a significant number of problems for the systems designer. As more and more advanced manufacturing systems are commissioned for service, it has become increasingly evident that the most difficult issues to resolve are not the technical and engineering problems of the equipment, but problems arising from the behaviour of the operator. And while many problems may be solved by simply revising the work layout or changing the structure of a task, as the use of 'state of the art' technology increases, it is clear the most difficult issues result from inherent limitations of the operator. The type of problem created by modern technology is clearly apparent in facilities like nuclear power plants. In the day to day running of these facilities, operators are required to process very large amounts of data (Craft, 1971). Moreover, under exceptional circumstances, decisions which could have critical or life threatening consequences must be made at short notice on the basis of these data.

At the same time, it is also evident that, as designers opt for more automation, the complexity of a system increases dramatically. And as complexity increases, successful operation becomes more and more dependent on the human factor; on intellect, creativity and the human ability to make the correct decision (Margulies & Zemaneck, 1982). The inherent problems associated with the complexity of manufacturing plants are obvious in industries such as chemical processing and nuclear power generation. The manufacturing processes in these plants are, by nature, not only complex but also extremely hazardous. In the event of a systems failure, the consequences for both humankind and the environment are potentially catastrophic. And again, the problems faced by the systems design team are not of a technical nature, but how best to allocate, with regard to both safety and efficiency, the various functions to either man or machine (Singleton, 1971).

Moray (1969) succinctly pointed out that as ". . . man spends increasing amounts of time interacting with machines, or with other men through the intermediary of machines, and as the amount of communication and control in the world increases, it becomes increasingly apparent that the weakest link in the flow of data and command is man" (p. 16). Thus, to utilize the operator in a man-machine system effectively, it is essential that we develop a coherent and detailed understanding of human information processing. This requires a human information processing model capable of predicting, not only the behaviour of a skilled operator in a complex environment, but also, one sufficiently detailed to indicate the general limit to cognitive performance. Only when we understand the fundamental issues relating to the basic organisation of the human decision mechanism can the more idealistic goals of predicting behaviour be addressed.

1.2 *Aspects of cognition*

A fundamental problem facing experimental psychology is to understand the cognitive processes that characterize human behaviour. Cognition is defined as the mental processes by which knowledge is acquired. The study of cognition, or cognitive processes, in its broadest sense includes the study of perception as well as the processes by which the operator detects and interprets information received from the external world by the sensory receptors. It also includes the study of the mental processes such as thinking, problem solving and reasoning.

A term widely used in the literature on cognition, and particularly when describing mental operations, is *attention*. It is interesting to note that the concept of attention is used in a number of different ways; Moray (1970), for example, suggested that there are at least six different meanings of the term in the psychological literature. However, two meanings are by far the most common; one is selective processing (Posner & Boies, 1971) and the other mental effort (Kahneman, 1973).

The *selective processing* aspect of attention was thought to be important by Luria (1976) who emphasized its role in the control of mental processing. He proposed that the ". . . *directivity and selectivity of mental processes*, the basis on which they are organised, is usually termed *attention* . . . By this term we imply the factor responsible for picking out the essential elements for mental activity, or the process which keeps a close watch on the precise and organised course of mental activity" (p. 256). It is evident from this definition that Luria considered attention to be a higher order cognitive function; the element of mental activity primarily responsible for selecting and organising the perceptual mechanism so that the most important features (of a task) are closely monitored.

The interpretation of attention as *mental effort*, however, is rather more contentious. According to Kahneman (1973), attention, mental effort and capacity are synonymous terms. In his preliminary discussion of the basic issues of attention, Kahneman outlined what appears to be the idea behind mental effort. He accepted that there must be a component of attention involved in the control of behaviour, since organisms can selectively attend to a particular stimulus in preference to others. Nevertheless, he asserted that attention involves more than mere control and selection. There is also a comprehensive aspect of attention which concerns amount and intensity; in other words, *mental effort*. In contrast, the sense in which Kahneman used the term *capacity* is far from clear. It is apparent that he considered capacity to be of particular relevance to theories of perceptual processing, an issue which will be discussed in much greater detail later.

Although the concept and particularly the definition of attention has attracted considerable debate, its use in the cognitive literature still abounds. Criticism has been directed mainly at the difficulty of precisely defining attention. It has often been pointed out that a definition of attention in terms of mental effort or capacity does not substantially increase our understanding of the concept; it merely restates the problem in other terms (Kantowitz, 1985). However, there is no denying that attention and the concepts related to it, particularly capacity, have played an important role in the development of cognitive psychology.

Consistent with the two major interpretations, there have been two main approaches to the study of attention. The first considers the selective (or focused) nature of attention; that is, the subject's ability to select a single dimension of a stimulus, or one aspect of a message, and to filter out all other irrelevant information. Studies of the selective role of attention have had a major influence in shaping some important features of information processing models, particularly the theory proposed to account for the structure of short-term memory. The second approach examines the way in which the individual deals with two sources of information simultaneously. This approach, generally considered under the rubric of divided attention, has also had a major influence on the development of certain aspects of cognitive psychology, such as the application of information processing theory to human factors engineering (Wickens, 1980) and the study of mental workload (Moray, 1979).

Both selective and divided attention tasks involve the simultaneous presentation of two (or more) signals. The main difference between a selective attention task and a divided attention task lies in the instructions given to the subject about the way they should perform the task. In a selective attention task, the subject is generally asked to select one stimulus from a set of stimuli, and subsequently respond to that stimulus on the basis of some distinguishing feature or dimension while ignoring other irrelevant features of the presentation. Divided attention, on the other hand, requires that the subject attend to both stimuli at the same time, and subsequently respond to each one appropriately.

One of the most important results obtained from the study of divided attention is that subjects are frequently unable to report the details of, or respond to more than one of a pair of stimuli which are presented simultaneously. This effect, known as dual-task interference, has been shown to occur over a wide range of conditions in the visual, auditory and tactile modalities, and with a variety of stimulus materials including letters, words, symbols and tones. The effect has also been demonstrated in a variety of different paradigms; experiments on dichotic listening (e.g. Broadbent, 1958), reaction time (RT) tasks (e.g. Welford, 1952), probe RT (e.g. Posner & Boies, 1971), manual tracking tasks (e.g. Vince, 1948) and visual detection tasks (e.g. Eriksen & Spencer, 1967).

However, not all experimental tasks that involve the presentation of two concurrent stimuli result in interference. A number of researchers (e.g. Allport, Antonis & Reynolds, 1972; Treisman & Davies, 1973) have argued that tasks that do result in interference somehow require the use of a common processing mechanism or processing facility. Thus, it is possible, by carefully selecting suitable experimental procedures, to determine which tasks (and perceptual processes) require the use of a common analysing mechanism, as opposed to those that must be analysed by separate mechanisms. Information about which tasks converge on common processing mechanisms and which tasks do not may then be used to map the important features of cognitive processing. In certain circumstances, depending on the experimental paradigm, this method of study may also be used to determine whether specific features thought to be part of the information processing mechanism, such as central bottlenecks, are responsible for task interference.

The aim of the present sequence of experiments was to investigate the nature of cognitive processing when two signals are presented simultaneously to different sensory modalities, one signal presented to the auditory, and the other to the visual sensory modality. In particular, these studies attempted to assess whether the interference effects commonly found to occur in other dual-task studies in which stimuli are presented in the same sensory modality also occurs across modalities. The predictions of a number of human information processing models were tested using the dual-task technique, in particular, the original models proposed by Broadbent (1958), Moray (1967) and Welford (1967), and the more recent resource model proposed by Navon and Gopher (1979, 1980), each of which is typical or representative of a general class of model.

1.3 Communication theory

Before discussing information processing models in detail, it is useful to review the circumstances that led to the original information processing concept around 1940. At that time, shortly after the start of the Second World War, rapid advances were being made in the use of process control technology. Efficient use of devices associated with high speed aircraft, sophisticated weapons, radar systems and other defence equipment developed during the war required a high degree of skill on the part of the operator. As the war progressed, it became increasingly obvious that, regardless of the selection procedure or the degree of training given, operators were encountering problems in controlling the equipment with which they had to work; for the *new* technology to reach its full potential, it was necessary to develop a better understanding of the parameters effecting human performance.

Shortly after the end of the war, a paper on the theory of communication by Shannon (1949) outlined in a clear and concise manner the nature of information and established the principles on which the information sciences were later founded. Shannon viewed information as simply *choice* or the narrowing down of alternatives. He developed the mathematical theory of communication essentially to deal with the transmission of 'messages' over *channels*. At the same time, psychologists working at Cambridge on the nature of vigilance and tracking proposed a model of skilled performance that likened the behaviour of the operator to that of a machine system controlled by an intermittent correction servo, similar to the operation of an electrical system with a positive feedback mechanism (Craik, 1948).

A number of aspects of the communication theory proposed by Shannon were seen as particularly relevant to the study of human skilled performance. In particular, the fact that information could be described quantitatively in terms of binary units (the *bit*) was viewed with great optimism, since it offered the promise of a definition of the capacity of a system in terms of a quantitative measure of information. Additionally, the concepts of *flow of information* and *limited capacity* were also recognised as consistent with the contemporary view of the cognitive processing mechanism and these concepts therefore influenced the acceptance of the mathematical theory of communication by psychologists.

Although the initial promise held for an information processing theory based on the measure of information has generally failed to materialize, another branch of the information sciences, computer programming, has had much more to offer. The computer program basically provides a recipe that outlines the formula for manipulating information, that is, for the selection, processing and outputting of information. The computer program is analogous to cognitive theories in the sense that it defines the formula for transforming information (Neisser, 1967). However, there was one other significant benefit from the program analogy; it provided the psychologist with a large number of hypotheses on which to work.

1.4 Information processing models

Broadbent's limited capacity single-channel model.

The first comprehensive information processing model to consider human performance along the lines of a computer program similar to that proposed by the mathematical theory of communication was developed by Broadbent (1958, 1971). Essentially, Broadbent's model was based on three general conclusions drawn from selective listening studies (Broadbent, 1952; Cherry, 1953; Poulton, 1953); firstly, that processing is central rather than sensory; secondly, that the effects vary as the number of competing messages, and the number of choices vary; and finally, if information is discarded, it is not discarded at random (Broadbent, 1958).

In developing the limited capacity model, Broadbent assumed that analysis of cognitive behaviour could be described in terms of the flow of information, similar to the way in which a computer program is executed. Basically, his model consisted of a limited capacity portion of the central nervous system, preceded by a selective filter which would pass only some of the incoming data. The selective filter was assumed to protect the limited capacity mechanism from contamination by irrelevant or superfluous data. A *literal* or *buffer store* of limited duration, assumed to hold any excess information arriving by other non-selected channels, preceded the selective filter. Information that passed through the limited capacity portion of the system was consolidated in a second short-term memory before being transferred to a more durable long-term memory store.

In a revised version (Broadbent, 1971), the flow of information and structural features of the model first outlined by Broadbent (1958) remained essentially unaltered but some aspects, particularly those relating to erroneous performance and unreliability, were changed. These revisions were intended to account for a number of new experimental findings. In particular, Broadbent considered the filter mechanism to act as a *pigeon hole*, categorizing data based not only on features of the stimulus, but also on the probability of occurrence of certain stimuli and on previous category states. The revised model also considered the role and effect of external factors, such as motivation, drive and stress, on performance of the system.

For the present discussion, three important features of Broadbent's model were (i) the concept of flow of information which presupposes a serial or sequential process; (ii) the concept of a literal or buffer store of brief duration to hold raw data; and most importantly (iii) the idea of a limited capacity mechanism in which data transmitted from the sensory receptors are coded or transformed before being passed to a permanent or durable long-term memory store. This concept of a limited capacity mechanism was to become an intrinsic part of those information processing theories known generally as limited capacity models. However, before considering the issue of capacity in more detail, we will look briefly at another type of limited capacity model in many ways similar to Broadbent's model.

Moray's limited capacity model.

As we have indicated, the operation of the processing mechanism proposed by Broadbent (1958) can be interpreted as either a single-channel mechanism with a filter which limits the amount of information entering the central processor, or alternatively, for data that gains access to the central mechanism, as a limited capacity processor. In contrast, a model proposed by Moray (1967), rather than filtering out data, allowed all of it to reach the limited capacity central processor. Thus, Moray's model, in this sense, can be considered one of true limited capacity.

Moray (1967) argued that the human operator functions not as a limited capacity channel in the way a transmission line functions, but as ". . . a limited capacity central processor whose organisation can be flexibly altered by internal self programming" (p. 85). Furthermore, he noted that a study by Mowbray and Rhodes (1959) showed that the difference between RTs for 2, 4 and 8 choice tasks could be abolished by practice; similar results had also been found for measures of RT that involve highly compatible tasks (Leonard, 1959; Davis, Moray & Treisman, 1961). Moray inferred from the results of these studies that practice or compatibility seemed to indicate a limitless channel, in the sense that channel capacity can be expanded significantly. Further, he argued that the results from these studies indicated that there is no narrow 'throat' or point at which data must be held in store. Therefore, while the convergence or filter model may hold in some conditions, it did not hold for all.

Moray asserted that the processing mechanism should be thought of, not as a transmission line of limited capacity which is a passive carrier of messages; but rather, a central processor of limited capacity which receives, transforms and generates messages. Moreover, he argued that it is the function performed on the messages, rather than the messages themselves, which uses up the capacity of the transmission system. Therefore, while the overall size of the processor is limited, its capacity can be divided up or allocated to different tasks according to the requirements of the task. Thus, the task determines where the channel is narrowest by its demands for capacity; that is, the demands a task places on various mechanisms limit the overall processing capacity and efficiency.

Moray concluded that the operation of the information processing system is constrained, not by the structure of the processing mechanism, but by the capacity that is available for the task. When the total capacity is not exceeded, tasks may be processed in parallel, as indicated by the results of RT studies involving practice and compatible tasks. However, at some stage of processing, either because of the difficulty of the task, or the sheer demand for capacity of the combined tasks, parallel processing will fail.

Channels and Capacity.

To appreciate the intricate nature of limited capacity models, it is essential to have in mind a clear definition of the terms used to describe the operation of information processing mechanisms. The operation of limited capacity models is usually described in terms of *channels* and *capacity*. In his initial proposal of the limited capacity single-channel model, Broadbent (1958) assumed that the whole nervous system acted, to some extent, as a single-channel with a limit to the rate at which it could transmit information. This limit Broadbent (1971) later termed 'a limit to capacity'. The meaning implied by the original concept was relatively specific; namely, that the ability of the single-channel to perform *complex* or *demanding tasks* is limited. However, two important points emerged from Broadbent's discussion of capacity. Firstly, in his view, the limit is the *rate* at which information or data can be transmitted. Secondly, limited capacity is only relevant to a particular structure; namely, the central nervous system, which he suggested behaves as a single-channel. It is clear from Broadbent's discussion that he believed that the concepts of capacity and channels are intricately related to one another; therefore, both assume an important role in most information processing theories.

The channel, according to Broadbent, is the mechanism through which information is transmitted, similar to the concept of a transmission channel originally proposed by communication theorists in the late 1940s. Broadbent (1958) assumed that the single-channel portion of the central nervous system was primarily the mechanism responsible for dual-task interference. He argued that the perceptual mechanism involved a system in which a number of input channels (the sensory inputs) converged onto a filter or switch from which only one input at a time could be selected for further processing through the limited capacity channel. Moreover, he claimed that data that were not selected at the filter stage of processing did not gain access to the single-channel mechanism and were subsequently *lost* from the system.

A different conception for a channel was proposed by Treisman (1969). She believed that the concept was particularly useful for the study of focused and divided attention. Following the initial work on the structure of the selective filter (Broadbent, 1954), a number of studies (e.g. Moray & Barnett, 1965) had shown that inputs arriving at the filter could be selected on the basis of aspects of a message that were not necessarily anatomically defined. In other words, selection based on dimensions or features of the message, such as the spatial positioning of a visual display or the semantic content of a message, frequently takes place. This led Treisman (1969) to suggest that features such as colour, orientation, pitch, loudness and the spatial location of a stimulus set or message may define a functional channel. Nevertheless, she also recognized that sensory data from separate modalities were processed, at some stage, though a common or shared central channel such as the single-channel proposed by Broadbent (Treisman & Davies, 1973).

However, not everyone shared Treisman's opinion that the notion of a channel was a useful concept. Kantowitz (1985), for example, seriously questioned the use of the term channel and considered it, to some extent, redundant or even unnecessary. He suggested that, while capacity can exist without the precise specification of a channel, a channel can only be inferred from the measurement of capacity. Although he considered that the concept of a channel was not strictly necessary, it nevertheless offered a convenience, in the sense that it is difficult to understand the term capacity without having some idea of where the capacity actually resides. Notwithstanding this, Kantowitz was clearly of the opinion that capacity was the more important concept.

While Kantowitz did not elaborate further on the conveniences the channel offered, it is evident that theories that postulate the existence of channels are 'more testable' in the sense that they are capable of generating a large number of testable predictions, whereas theories that deny the existence of channels generate very few. One reason for this is that channel models typically postulate an information processing mechanism that consists of a number of stages, with each stage capable of communicating with other stages via a channel. In other words, it is assumed that data are transmitted along a predetermined pathway from one processing mechanism to the next. Further, each stage of the information processing system is supposed to consist of a distinct mechanism or control a specific operation and may therefore be considered as a separate entity. Hence, the predictions of channel models can be empirically tested by manipulation of parameters such as the complexity or difficulty of the task. From this point of view, theories that involve the channel concept are likely to lead to a greater understanding of cognitive processing than theories that do not.

The testability of the channel concept is related to process separability - the assumption that two processes that act separately in an organism are independent of each other and therefore define two distinct channels (Garner & Morton, 1969). Conversely, this implies that if two processes interact in such a way that each process limits the performance of the other, they are assumed to be correlated in some way and therefore define a shared channel. The theories of perceptual independence and process separability are intricately related to the study of divided attention and, in particular, the issue of capacity. They will each be considered in much more detail later in this review.

It is evident from the foregoing discussion that a channel is an integral part of the information processing mechanism. It is also evident that the concepts of channels and capacity are more or less interrelated. One view, which has already been stated, assumes that the channel is the *source* of capacity in the sense that the capacity of the information processing system is contained in a channel (Kantowitz, 1985). A similar connotation of the relationship between the two concepts is evident in the phrase *channel capacity* used by Sanders (1979). He suggested that the central theme of this term is that capacity is constant and is defined by the channel; hence, the *human channel capacity* defines the upper limit of mental processing.

However, the role of channels and capacity is not always so clearly defined. The issues surrounding capacity were discussed at length in a review of models of central processing written by Schweickert and Boggs (1984). They suggested that, in addition to transmitting information, the capacity of a resource is a measure of its ability to store and transform information. They also proposed that resources are probably used in combination, thereby making it difficult to determine the individual capacity of each *resource*. While they considered resources to be devices such as memory mechanisms, switches and channels, they did not give a clear indication of the precise meaning or role of a switch or channel. However, they did suggest that a channel involved the use of a central mechanism, the interpretation previously emphasized by Broadbent (1971).

On the other hand, Kahneman (1973) stressed the importance of the concept of capacity to information processing models, although, as we have previously discussed, he suggested that a number of terms should be interpreted as meaning essentially the same thing as capacity. Kahneman suggested that successful cognitive processing required two inputs; one information input specific to a processing structure; and a second non-specific input that he described as *mental effort, capacity* or *attention*. Further, he proposed that the non-specific input was controlled by the level of arousal associated with a given task; that is, the level of alertness, vigilance or responsiveness required to perform the task.

Kahneman's view of *capacity* differed from Broadbent's traditional definition in a number of significant ways. While Kahneman considered the total amount of capacity to be limited, he suggested that the capacity allocated to perform a task varied with the complexity or difficulty of the task. More difficult tasks were allocated more capacity, while easier tasks were allocated less. Kahneman suggested that a rise in the demands of activities caused an increase in the level of arousal, as well as a subsequent increase in *mental effort* or *capacity*. Moreover, he argued that it was impossible to expend more than a certain amount of effort on simple tasks. As a general principle, Kahneman (1973) proposed that ". . . the effort invested in a task is mainly determined by the intrinsic demands of the task, and that voluntary control over effort is quite limited" (p. 15). Therefore, according to Kahneman, the intentions of the performer appear to have little influence on the amount of effort that can be applied to a task. While Kahneman acknowledged that spare capacity could be allocated to a second task, he asserted that the amount available decreased with increasing involvement in a primary task. Furthermore, he also argued that interference between tasks occurred because of the involuntary control over the capacity applied to tasks.

A different approach was proposed by Townsend (1975) who noted that *capacity* refers ". . . to the distinction between channels that take more time or make more errors as the number of inputs increases as opposed to those that do not" (p. 158). He considered the question of capacity from two different perspectives; the limited-unlimited capacity issue and the serial processing-parallel processing issue. According to Townsend, the limited versus unlimited capacity issue involved the processing efficiency of the system; whether performance, ". . . in terms of speed or accuracy, is degraded or is unaffected when increased numbers of elements are input to the system" (p. 135). While Townsend recognized the problems associated with the concept of capacity in terms of the effectiveness or efficiency, he also conceded that there was only one effective way to measure capacity; that is, to estimate changes in performance accuracy or time lag with changing processing requirements.

The second issue, that of serial processing-parallel processing, is concerned with the *nature* of the capacity of a system. According to Townsend (1975), a serial system is one that processes elements one at a time, completely processing one element before beginning the next. On the other hand, a parallel processing system processes elements simultaneously, without any apparent delay between the start and end of processing. The question that arises from this issue is whether capacity can be divided simultaneously amongst all the inputs, or whether it is concentrated on one input at a time. A serial processing system, for example, assumes that capacity is applied to the elements one at a time, while a parallel processing system assumes that capacity is divisible and, as such, is applied to the elements simultaneously. Moreover, Townsend argued that the basic assumptions about the nature of the capacity of each system differ significantly. The capacity of the serial processing system, for example, is assumed to exist in the central processing mechanism. On the other hand, each separate function in a independent parallel processing system may be assumed to have its own source of capacity which can be allocated concurrently to activities as required.

While a number of alternative views of capacity have been proposed, there has been general agreement among capacity theorists about several aspects of the concept. Thus, it is generally accepted that, at some stage of processing, there is a limit to the rate at which information can be processed. Whether this is purely the result of limited capacity, or it arises from other features of the processing mechanism is, however, problematical. Further, it is also assumed that the mechanism primarily responsible for the difficulties associated with divided attention is central rather than peripheral, although there is not consistent agreement that limited capacity is the sole cause of the divided attention deficit. It is also evident that capacity is effected by a number of external factors such as motivation and arousal, and that some common methodological problems are at least partly the result of the interaction between these external factors and *internal factors* such as capacity.

However, although these theoretical issues have met wide acceptance for the past 20 years, there are a number of other questions about capacity that are yet to be resolved. For example, an important question is whether capacity resides in a single undifferentiated source that is shared between all cognitive processing activities and is therefore distributed to perceptual mechanisms as required; or whether each perceptual mechanism has its own specific source of capacity? Further, if there is a common source of capacity, can it be applied to more than one perceptual mechanism at a time; or are there certain aspects of perceptual processing that can only be handled one at a time? Answers to these questions about the nature and role of capacity, which are essential to understanding cognitive processing, form the central theme of the present thesis.

1.5 Skilled performance

The concept of the operator as a single-channel mechanism originated with the work of K.J.W. Craik, the first Director of the British Medical Research Council's Applied Psychology Research Unit at Cambridge. During the course of the Second World War, Craik recognized the need to understand factors that limited the performance of operators engaged in activities such as gun laying and radar scanning. Craik was particularly interested in tracking performance and viewed the behaviour of operators involved in manual tracking tasks as a skill. However, the sense in which psychologists of the 1940s used the term *skill* was rather different from the earlier traditional view (Bartlett, 1947). Prior to the war *skill* had largely been considered in terms of specific aspects of the conduct of a trade or craft, acquired during a lengthy period of training, and which involved "... knowledge, judgement, accuracy and manual dexterity" (Welford, 1967). As a result of technological developments that occurred during the war, however, the need to understand the limits of the human performance led psychologists to consider fundamental aspects of cognitive performance as central to an understanding of skilled behaviour; aspects such as the ability to perceive and discriminate signals, to analyse complex data and to make decisions.

Craik's understanding of skilled performance developed mainly from manual tracking studies conducted using an instrument known as a kymograph, a device which displayed an irregular moving line to simulate the operator's task when tracking a moving target. Essentially, the kymograph consisted of a rotating drum to which a paper band was attached. A portion of an irregular moving line, drawn on the paper band, could be viewed through a narrow slit in a panel covering the instrument. The operator was required to trace, as accurately as possible, the path of the moving line using a pointer controlled through a mechanical lever or steering wheel, with the aim of minimising the error between the moving target line and the pointer (Bertelson, 1966).

Two short papers written by Craik and published posthumously shortly after the war (Craik, 1947, 1948) outlined a theory of skilled performance based on the results of studies of manual tracking carried out in the early 1940s. These studies indicated that, regardless of the degree of movement exhibited by the target, the operator's responses were characterized by a *jerky* trace, with corrective actions typically initiated at intervals of about 0.5 sec. Craik concluded that the intermittency resulted from an inherent limitation within the processing mechanism, rather than because of a discrepancy or error between the moving target and the pointer. Furthermore, it was clear that once a correction was initiated, some controlling process ran a *complete cycle* before further corrections could begin.

Craik's theory interpreted the behaviour of the operator in mechanical terms, as an element in a control system; an element that mediates between sensory input on the one hand, and the selection and output of a rational response on the other. The operator's behaviour, Craik suggested, was analogous to a mechanical device known as an intermittent correction servo. The characteristics of this mechanism are that corrections made when performing seemingly continuous actions are actually discrete and limited in rate. On the basis of empirical evidence, Craik argued that the intermittency in the perceptual system between successive corrections was approximately 0.5 sec, supposedly due to the time required for the selection of a response. Craik also suggested that the selection process taking place in the cortex of the brain involved a *switching* mechanism to protect the execution of current activities from interference by subsequent signals entering the brain. In other words, the decision process was held to be discrete in the sense that only one signal (or one set of signals) could be processed within a critical period of time.

Craik noted the analogy between the delay in the response to a second signal (S_2) that occurred in RT studies and the refractoriness of neurons (Telford, 1931), suggesting that the intermittency or delay was akin to a *psychological* refractory period. Although it has been shown that the similarity between the two processes is quite superficial, the term *psychological refractory period* (PSP) has since been used to denote the delay that results when the operator is required to respond to the second of two stimuli which is presented a short time (typically less that 0.5 sec) after the first.

After Craik's untimely death in 1945, the study of *intermittency* continued at Cambridge University, mainly through the work of Vince and Hick. Apparently, many of Craik's initial thoughts about intermittency developed from work carried out in collaboration with his research student, Margaret Vince. During the presentation of his theory, Craik (1947) suggested that it may be beneficial to set 'unnatural' courses containing sudden changes in direction ". . . in order to reveal particular characteristics of the operator's performance" (p. 143). Following this lead, Vince (1948) used a series of step functions to simulate the presentation of *discrete signals.* Her results showed clearly that the RT to the second discrete signal increased markedly, a result which provided strong support for the intermittency argument initially proposed by Craik.

1.6 Single-channel hypothesis

The work regarded by many psychologists as the most authorative and influential treatment of central intermittency was that provided by Welford (1952, 1959, 1967). In his initial paper, Welford (1952) reviewed the most important PSP studies published to that time, including those of Mowrer (1940), Vince (1948, 1949), Hick (1948, 1949), Davis (1948) and the important theoretical papers of Craik (1947, 1948). Based on his interpretation of this previous research, Welford (1952) outlined a theory of skilled performance primarily intended to account for the psychological refractory period. One of the most important aspects of this theory concerned *organizing time* - the time required by the central mechanism to process information and initiate a response. Welford suggested that it did not matter whether a signal was preceded or followed by another; the central *organizing time* was essentially constant and, under normal circumstances, the same as the RT for a single response. Following a suggestion that attention is diverted to monitor stimulation of kinaesthetic receptors (Hick, 1948), Welford proposed that ". . . the central mechanisms are liable to become engaged by stimuli fed back from the response" (Welford, 1952, p. 18); in other words, the perception of feedback data was held normally to require central organizing time. However, the most significant element of Welford's theory was the proposal that no two *central organizing times* can overlap. He argued that, ". . . information from a stimulus arriving while information from a preceding stimulus is being dealt with has to be 'held in store' until the central mechanisms are free" (p. 18). Essentially, the proposal that no two central organizing times can overlap formed the cornerstone of Welford's single-channel hypothesis.

According to Welford, the basic elements of this hypothesis could be re-stated as a simple mathematical equation:

$$RT_2 = RT_1 + T_{O2} - ISI, \text{ for } ISI \leq RT_1$$

where RT_1 and RT_2 are the reaction times to the first and second signal, respectively; that is, the time between the onset of a stimulus and the beginning of the response movement;

T_O is the *central organizing time*; the time required by the central mechanism to deal with data from a signal and to initiate a response, normally assumed to be the same as RT for a single response; and

ISI is the time interval between the presentation of signals S_1 and S_2.

As well as providing a clear statement of the theory of skilled performance, Welford (1967) also suggested a model of the human sensory-motor system which contained the hypothetical *single-channel*. Welford's model, like the one proposed by Broadbent (1958), considered the human operator in terms of the flow of information. For a stimulus to be processed completely, it was assumed to have passed through three discrete stages of analysis. The first stage contained a number of sensory input mechanisms each capable of receiving and storing data from stimuli until the second stage was ready to accept and process these. However, data in the storage mechanism could only be held for a limited period of time. Welford suggested that decisions are based on data processed through a second stage; a limited capacity single-channel mechanism. Further, he argued that the capacity of the mechanism was limited ". . . in the sense that it takes a finite time to process information and can thus only deal with a limited amount of information in a given time" (Welford, 1959, p. 206). The third and final stage was responsible for co-ordinating and controlling the responding phase.

Welford contended that sensory input data can be accumulated in the storage mechanism while the decision channel is occupied dealing with previous data. The accumulated data can then be passed to the decision channel as soon as it is free. Moreover, the decision channel can 'issue orders' to the effector side for a series of responses, the execution of which can overlap with the decision channel's dealing with fresh input. However, Welford assumed that if data are fed back to the central mechanism during the responding phases, these would capture the decision mechanism for a brief period, and hence defer further processing of existing or fresh data until the feedback data had been dealt with. Thus, the mechanism responsible for the single-channel characteristics (or central bottleneck), and hence the refractoriness of the system was, according to Welford, the decision stage.

One of the ramifications of Welford's paper, particularly the mathematical formulation of the single-channel hypothesis, was the interest it aroused in the study of central intermittency. This interest subsequently led to a substantial increase in the amount of PSP research carried out in the late 1950s and early 1960s. It is interesting to note that a large percentage of studies initiated during this period reported results consistent with a limited capacity single-channel model. In an important review of studies involving intermittency, for example, Bertelson (1966) concluded that for simple reactions, when the second signal arrived during the reaction to the first, the data were consistent with the idea that the delay originates in a central bottleneck. However, when the second signal arrived after the end of the first reaction, the results were more confusing. Welford had suggested that when a second stimulus arrives shortly after the completion of the first response, the initiation of the second response would be delayed because the perception of feedback from the first response required central organizing time. While a delay in the second response was occasionally found, consistent with Welford's proposal, the most frequent result was either no delay, or a delay of much shorter duration than the proposed 150 ms required to monitor feedback.

Bertelson (1966) noted that the great majority of studies published to that time had concentrated on simple rather than choice reactions. He suggested that the results of studies involving choice reactions were inconsistent, perhaps because strategies played a more important role in choice reactions than for simple reactions. Although Bertelson considered the data from choice RT studies more difficult to interpret, he argued that choice reaction tasks were more representative of the decisions taken in skilled activities, so that a comprehensive theory of central intermittency must also be able to explain the outcome of tasks involving choice reactions. While the merits of studying choice rather than simple reactions were not discussed at length by Bertelson, it is apparent that he considered the study of tasks involving a variety of stimulus conditions, including complex choices, an important step in evaluating the validity of the single-channel theory.

Additionally, Bertelson's review underlined the similarity between Broadbent's limited capacity model and Welford's single-channel theory. Bertelson observed that the problem confronting the operator in a typical intermittency experiment is how to deal with irrelevant signals, a task which is essentially the same as that undertaken in selective listening studies. He argued that the operator can either allow the irrelevant signal ". . . to occupy the channel and start an intermittency interval which terminates with a decision not to respond" (Bertelson, 1966, p. 159) or, alternatively, refuse the irrelevant signal access to the channel. Bertelson suggested that the second alternative implied that the *switch* that Craik (1947) placed before the computing process must be more than a simple shutter. It must have the ability to select or discard classes of inputs and is therefore essentially the same function that psychologists have long called *attention*. Thus, according to Bertelson's analysis, Craik's *switch* and Broadbent's *filter* are both the same mechanism of *attention*.

Shortly after Bertelson's review was published, a number of studies that involved choice rather than simple RTs raised serious doubts about the theory of central intermittency. One of the first experiments to show the limitations of Welford's single-channel hypothesis was a study conducted by Karlin and Kestenbaum (1968). Their study was designed to test whether the predictions of Welford's equation still held when choice rather than simple reactions were involved. Subjects who took part in Karlin and Kestenbaum's study were assessed over five conditions involving simple and choice reactions for both the first stimulus (S_1) and the second (S_2). In condition 5-2 for example, subjects had to choose one of five alternative signals for S_1, and one of two for S_2. In the other four conditions the choices of S_1 and S_2 were 2-2, 1-2, 2-1 and 1-1, respectively.

According to the single-channel hypothesis, central processes concerned with two separate stimuli are not able to co-exist. Hence, data from a stimulus that arrives while the central mechanisms are processing data from a previous stimulus have to be *held in store* until the mechanisms have cleared (Welford, 1952). This idea is represented in Welford's equation as the *central organizing time* (T_O). It infers that, following the first response (RT_1), when the central mechanisms are free, a signal from the second stimulus is passed to the central mechanisms where it is fully processed in a time period T_{O2}.

Assuming T_{O2} is constant for a given choice reaction, but increasing as the number of choices increases, Welford's equation would predict that data from simple and choice reactions, each plotted in the form RT_2 (on the ordinate axis) versus ISI (on the abscissa), would map a series of parallel linear functions, with the intercept on the ordinate axis determined by the values of RT_1 and T_{O2}. In other words, according to Welford's equation the delay in RT_2 is basically a function of RT_1 and the central processing time for S_2; once the first reaction has been completed the remaining latency should be 'normal'. Therefore, the number of choices of S_2 should not have any effect on RT_2.

This prediction was tested by Karlin and Kestenbaum (1968). RT to the second stimulus (RT_2) measured for choice conditions 5-2, 2-2, and 1-2, and plotted as a function of the interstimulus interval (ISI) resulted in three approximately parallel lines; a result consistent with the predictions of Welford's equation. However, when the data from condition 2-2 and condition 2-1 were plotted and compared, it was apparent the outcome was not consistent with Welford's equation. Whereas the number of choices of S_2 should not influence the outcome, a significant difference was found. At short ISIs, the time between RT_2 for condition 2-2 and 2-1 was approximately 30 ms, but at the longest ISI (RT_1), the difference was close to 90 ms. Thus, the data obtained by Karlin and Kestenbaum for conditions 2-2 and 2-1 did not map parallel lines as expected on the basis of the single-channel hypothesis. Significant differences between the slopes of the lines for conditions 1-2 and 1-1 were also found.

Karlin and Kestenbaum looked at a number of possible interpretations to account for their results, such as a grouping strategy in which the subject delays the first response, waiting to determine what the second response will be. However, analysis of the function of RT_1 versus ISI indicated that this was unlikely to have occurred. In the final analysis they were led to suggest that "... the central channel while occupied with the first response may be able to process some kinds of information from the second response" (Karlin & Kestenbaum, 1968, p. 177). Further, they speculated that perhaps "... the basic process involved when RT_2 is simple cannot overlap with the refractory period produced by the first stimulus but some part of the additional selective processes involved in disjunctive relations can" (Karlin & Kestenbaum, 1968, p. 177). In other words, they considered that decisions about S_2, including the selection of a response, occurred concurrently with processing of the previous response.

A study by Kahneman (1973) using data from a previous PSP experiment raised further doubts about the validity of the single-channel hypothesis. Kahneman noted that although a large body of evidence indicated that attention was often divisible, the single-channel hypothesis was still regarded by many as the most appropriate human information processing model to account for the PSP effect. He suggested that this had come about largely because of the way data from PSP studies had been analysed with RT_2 as a function of ISI.

Kahneman (1973) proposed that it was 'equally reasonable' to analyse PSP data in terms of the interval between responses R_1 and R_2 (defined as IRI), as a function of the interval between the presentation of the two signals, S_1 and S_2. According to the single-channel hypothesis, IRI should be constant up to a value of ISI approximately equal to RT_1 plus the time required to monitor feedback, thereafter increasing proportionally with ISI. Further, the magnitude of IRI when ISI is less than RT_1 should be approximately equal to the average value of RT_2 plus the additional time required to monitor feedback.

Kahneman also argued that the latency of RT_1 should be independent of the complexity of the response required for S_2.

From choice reaction time data collected in a previous PSP experiment (Smith, 1969), Kahneman calculated

$$IRI = RT_2 + ISI - RT_1$$

for three different choice reaction conditions in which there were either 2, 4 or 8 choices for S_1, but only 2 choices for S_2. The data were plotted with IRI as a function of ISI. According to Kahneman, the outcome of this analysis drastically violated the predictions of the single-channel hypothesis for all choice conditions. The constant relationship predicted between IRI and ISI was not evident; rather, the slope of the function was linear and positively increasing with ISI. Moreover, the magnitude of IRI at short ISIs was significantly less than the average value of RT_2.

Kahneman argued that IRI indicates the basic timing of the response process. He pointed out that IRI was significantly less than RT_2 at short values of ISI, indicating that at least some processing of S_2 must have occurred at the same time the response to S_1 was being processed. Furthermore, Kahneman suggested that the positively accelerating slope of IRI supported this proposal since it indicated that the amount of attention devoted to S_2 increased steadily during the latency of R_1. Moreover, the same type of analysis of other PSP data indicated that this result was typical of a large number of other RT studies.

1.7 The detection paradigm

At the same time, data obtained using a two alternatives, forced choice detection method, developed to assess the amount of information processed in a finite time, raised important questions about the validity of the limited capacity concept. Briefly, this technique - known as the detection method -

involved the presentation of a display of alphanumeric characters for a short period of time. From the total set of up to 12 characters, a subset of two elements was designated as *targets*, the remaining characters being defined as *noise elements*. The subject's task was to discriminate the specific *target* element that appeared during a trial and subsequently respond as accurately as possible. In the initial detection method studies, the probability of a correct response was the dependent variable (Estes & Taylor, 1964, 1965). However, other studies using the same basic method have measured both the probability of a correct response as well as the RT (e.g. Estes & Wessel, 1966; Egeth, Jonides & Wall, 1972).

The initial argument against limited capacity serial processing models came from a study by Eriksen and Spencer (1969). They presented subjects with a circular array consisting of 10 letters. Each letter of the array was shown separately, for a duration of 2 ms and with a presentation rate ranging from 5 ms to 3 sec. The number of correct detections was recorded for each rate of presentation of successive letters (ISI). Eriksen and Spencer argued that a strict serial processing model would predict an input rate effect, so that performance would suffer at short ISIs, since processing capacity would have to be shared amongst the 10 letters. On the other hand, at ISIs of 3 sec, the subject would have time to process each letter individually, and therefore no processing limitation should be observed. The results showed that the input rate effect did not occur. Eriksen and Spencer (1969) concluded that subjects can ". . . scan through or encode nine letters as efficiently in 50 *ms* as in 25 *sec*." (p. 15). They suggested that the system must consist of either a multi-channel encoder or a series of filters to screen out irrelevant information. Regardless of the operation of the mechanism, in the final analysis they concluded that parallel processing of inputs must take place at some stage in the system.

While Eriksen and Spencer's argument for *unlimited capacity* was generally accepted, it was evident that there were a number of methodological problems with their experimental procedure. As Shiffrin and Gardner (1972) indicated, the displays with short ISIs were not actually simultaneous. Thus, it was possible that attention could be switched from one letter to the next, allowing sufficient information to be extracted and processed to discriminate the target accurately. Further, since no masking stimulus was used at any stage of the presentation, it is possible that information could be obtained from iconic memory well after the display of each letter had been turned off. It was also plausible that at long ISIs the previous letter acted as a mask and therefore the task with an ISI of 3 sec was of comparable difficulty to the task with short ISIs.

A series of experiments by Shiffrin and Gardner (1972) addressed the problems associated with Eriksen and Spencer's study. Their task involved the letters T and F as target elements, and the letter O as the *noise* element for a low confusability task; and the same target elements but a hybrid character derived from these letters as the *noise* element for a high confusability task. The elements were arranged in a 2 x 2 matrix, and presented both simultaneously (with four elements at the same time), or sequentially (with either individual or pairs of elements presented in sequence). The main difference between the three experiments was the number of elements per display in the sequential condition. For each condition, the information available was controlled by a mask designed to eliminate potential problems associated with iconic memory. Subjects were required to report the target letter presented as well as its position in the matrix.

The results Shiffrin and Gardner reported were reasonably consistent throughout the three experiments conducted. They indicated that the level of confusability significantly effected both letter detection and location judgement. However, the mode of presentation generally had no effect, although the results of Experiment II, which appears to have been a pilot study, did show a small but significant difference between simultaneous and sequential presentation.

Shiffrin and Gardner concluded that the performance of simultaneous and sequential tasks was essentially the same. Further, they indicated that there was no evidence that internal switching of attention occurred. They argued that processing to the level of letter recognition takes place without capacity limitation and that attentional control does not operate in visual perceptual processing. Further, they indicated that this supported a model in which information enters the visual field and is processed perceptually without limitation or attentional control, up to and including at least the level of letter detection.

However, it was not long before the view that information could be processed without limitation or attentional control was challenged. Hoffman (1978), for example, found evidence for parallel processing, but only when targets were highly discriminable from non-targets or noise items. A study by Shiffrin and Schneider (1977) showed similar results. They observed parallel processing when sets of targets and non-targets were distinctly different from one another and well learned in long-term memory. Under these conditions, Shiffrin and Schneider suggested *automatic processing* occurred; that is, performance characterized by a low demand for attention and virtually unaffected by the processing load. However, when the tasks consisted of targets that were not well learned, selection involved a serial *controlled search process* that was highly demanding of attention and therefore of limited capacity. To account for these exceptions to parallel search, a number of similar two-stage models of attentional selection were proposed (e.g. Duncan, 1980; Hoffman, 1978; Schneider & Shiffrin, 1977).

In the two-stage model proposed by Duncan (1980), simultaneous stimuli are examined, during the first stage of processing, in parallel without the effects of divided attention. Stimuli are identified in full, using well learned information derived from memory. At the same time, naming and classification also take place. However, Duncan (1980) emphasized that at the first level, none of the information derived could serve as the basis for the selection of a response because no "... reportable perception of any sort has yet been formed" (p. 284). It is not until the second level of processing that a reportable perception is created and the subject is aware of the target. Further, it is at this stage that capacity limitations occur, in as much as the second level cannot store or report an infinite number of stimuli. Therefore, the first stage served as a basis for access to a second limited capacity stage of processing. It is at the point of access to the second stage at which the stimulus enters the subject's awareness. Because two-stage models typically ascribe little or no role to attention at the early stages of processing, they have been characterized as *late selection models*.

Nevertheless, the view that selection takes place late in stimulus processing is not universally held. Broadbent's (1958) original limited capacity model, for example, assumed selection takes place at an early stage. More recently, the question of selection has been considered from a different perspective (Eriksen & Yeh, 1985; Pashler, 1984b; Pashler & Badgio, 1985), culminating in the proposal of an *early selection theory*. According to Pashler (1984b), early selection theories assume selection takes place on the basis of certain criteria, for example, the spatial location, or features such as the orientation of lines. Therefore, the selection process is assumed to precede identification of the stimulus. Support for early selection comes from a number of sources, one being a study by Treisman and Riley (1969). They had subjects shadow one of two dichotically presented lists of words. Throughout the presentation, subjects were required to detect targets words in either ear. The results indicated that detection was greater in the shadowed ear than in the non-shadowed ear. However, as Treisman and Riley (1969) argued, if selection were not possible until some pre-analysis of *all* concurrent stimuli occurred, then why should targets be easier to detect in the shadowed list?

Evidence for the view that information can be processed in parallel by a number of 'independent special processors' was also forthcoming from a number of other studies, including one carried out by Allport, Antonis and Reynolds (1972). This study has been particularly influential and it has been frequently cited as strong evidence for the view that attention can be divided between concurrent tasks. Allport *et al.* argued that the controversy surrounding the single-channel concept was essentially restricted to two main issues; the level at which selection between competing messages or tasks becomes necessary; and the adequacy with which competing or irrelevant messages are rejected. They noted that most studies investigating the single-channel concept required simultaneous attention to two closely similar or even identical tasks. Allport *et al.* claimed that the problem confronting subjects is not the result of a capacity limit, but rather the difficulty of keeping two similar but unrelated signals separate.

To test this hypothesis, Allport *et al.* carried out two experiments that involved the concurrent presentation of a combination of both visual and auditory tasks. In their first experiment, an auditory shadowing task was paired with a discrete competing task; either visually presented words, auditory words or colour photographs displayed on a screen for 1 sec.

Shadowing performance was monitored by tape recorder throughout each three minute trial and subsequently evaluated for errors. Following each trial, the amount of information processed from the competing task was assessed by means of a forced choice recognition memory test.

The results of this study indicated that recognition memory of items presented as competing tasks differed for each mode of presentation. Recognition of auditory words, for example, had the highest error rate; approximately 50%. On the other hand, recognition of the colour photographs was extremely good, with an error rate of only 9%. Allport *et al.* suggested that the results of Experiment I were not easily reconciled with the single-channel hypothesis, since according to that theory, ". . . inputs to long-term memory must pass through the general purpose single-channel. If this is already fully occupied by the shadowing task, then merely altering the modality or other characteristics of the secondary input could not affect the latter's chance of gaining entry to long-term memory" (Allport *et al.*, 1972, p. 229). They also considered an explanation based on time-sharing on a single-channel, but concluded that this option did not appear plausible, since it could only account for the results of the shadowing task paired with the presentation of pictures. Their argument was basically that a time-sharing strategy would be most easily applied to discrete tasks such as auditory words paired with shadowing. But the results were not consistent with this proposal; the combination of auditory words and shadowing resulted in the highest error rate. Allport *et al.* followed up their first experiment with a second, specifically aimed at evaluating the option of time-sharing.

The second experiment conducted by Allport *et al.* used a similar auditory shadowing task, but in combination with a continuous (rather than discrete) competing task which consisted of playing while sight reading selected piano pieces. There were two performance levels for each task; easy and difficult. The easy auditory shadowing task consisted of text derived from an anthology of humorous narrative prose; the text for the difficult task was taken from writings of early Norse history. Similarly, the easy music task consisted of piano pieces selected from a Grade II music examination paper, while the pieces for the difficult task were selected from a Grade IV examination paper.

The results of Allport *et al's* second study indicated that subjects were able to play the selected piano pieces with the same precision while maintaining shadowing performance in both the divided and undivided attention conditions. Furthermore, their retention of both easy and difficult prose was high. The average recognition test scores for the difficult prose paired with Grade II and Grade IV piano playing were 61% and 56%, respectively. This outcome compared favourably with the average score for the same condition with undivided attention, which was 57%.

Allport *et al.* concluded that auditory speech shadowing and piano playing could be combined with little or no loss of efficiency in either task. They argued that the results of both experiments indicated that the division of attention did not unduly affect performance on the subsequent memory recognition test. Subjects performed equally well in both the divided and undivided attention conditions. Furthermore, in their opinion ". . . the results of the sight reading experiment are wholly incompatible with the single-channel hypothesis" (Allport *et al.*, 1972, p. 232)

However, while Allport *et al's* conclusions have apparently been widely accepted, they should not be accepted without question. One issue, briefly covered by Allport *et al.*, concerns the variability in the performance of the music students in Experiment II. This is particularly important because the results of this experiment are central to Allport *et al's* general conclusions about the division of attention. They indicated that the most skilled pianist achieved a score of 81% when questioned about the content and meaning of the passages of prose shadowed; on the other hand, ". . . the least proficient sight reader amongst [the] subjects answered only 14% of the same questions correctly" (Allport *et al.*, 1972, p. 232).

This raises an important question about the nature of the skills involved in piano playing and sight reading. It is well documented that a sufficiently practiced motor skill, such as the motor aspects of piano playing, may be autonomous, in the sense that it becomes highly efficient and can be executed more or less in an automatic fashion. Further, at the highest level of performance, a motor skill becomes relatively immune to sources of interference, and thus two or more tasks may be carried out proficiently without serious disruption to the principal task (Ellis, 1972).

However, this is not to say that piano playing is a mere repetition of notes performed in an automatic fashion. This type of skill involves a number of other physical and cognitive factors, requiring both reasoning, imagination and the ability ". . . to *see music*, . . . its Shape, Feeling and Time-spot" (Matthay, 1913, p. 13). It also evident that these abilities gradually develop over a long period of training. The range of musical skills includes subtle techniques such as learning to analyse and read music in phrases rather than notes, similar to the way in which a child learns to recognise words from a series of letters. This skill was recognised by Craik (1948), who indicated that high speed performance such as that exhibited by skilled musicians could be accounted for by grouping; that is, by combining a series of elements together into a meaningful unit. In the case of musical performance, an element of music is defined in terms of phrases rather than notes. Thus, it is possible that the competent pianist was able to score highly when questioned about the shadowed prose because he was able to perceive a musical phrase from the piece being played in a relatively short period of time compared with the duration of the phrase. The 'free' time could then have been used to process additional information, such as the shadowed prose. The point is that the skills that musicians acquire through a long period of practice are precisely those required to divide attention successfully. It is quite probable that the skill of dividing attention is reflected in Allport *et al's* results from this study.

Support for the view that division of attention is a learned skill also came from a study by Spelke, Hirst and Neisser (1976). They had two subjects practice writing dictation while reading short stories five times a week for 17 weeks. After extensive practice, subjects were ". . . able to copy words, detect relations among words and categorize words for meaning, while reading as effectively and as rapidly as they can read alone" (p. 226). However, prior to achieving this level, the subjects apparently went through a period during which performance of the writing task was 'automatic'; that is, it could be performed without interference from a concurrent alternative activity. Further, at this stage, Spelke *et al.* suggested that the dictation task did not require 'higher order attentional skills' and therefore no semantic analysis of the dictation was performed. They contended the division of attention was based on developing and using situation specific skills. Spelke *et al.* concluded ". . . Studies of attention which use unpracticed subjects, and infer mechanisms and limitations from their performance, will inevitably underestimate human capacities. Indeed, people's ability to develop skills in specialized situations is so great that it may never be possible to define general limits on cognitive capacity" (p. 229).

These results were replicated in a subsequent study using essentially the same experimental techniques (Hirst, Spelke, Reaves, Caharack & Neisser, 1980). Hirst *et al.* conducted two experiments, one to determine whether the redundancy of the reading text affected the division of attention; and the second to test Spelke *et al's* hypothesis that performance on the writing task is 'automatic' and without semantic analysis. They concluded that the ability to divide attention was primarily a skill. Further, they suggested capacity limits may explain unskilled performance, but not the achievements of practiced individual.

Therefore, according to the 'skills' approach, the assumption of limited capacity was unwarranted for tasks performed by highly practiced subjects. Moreover, Hirst *et al.* argued that dual-tasks can be performed in parallel provided the two concurrent tasks can be effectively segregated. Where difficulties arise with dual-task performance, interference is assumed to occur between 'parallel lines'. This interference was described by Hirst *et al.* as 'cross talk'. Subsequently, Hirst and Kalmar (1987) argued that there is more interference or cross talk with related tasks than with unrelated tasks. As a result, it is easier to attend to a visual and auditory message than either two visual or two auditory messages, since selection amongst competing inputs depends on the ease with which each can be discriminated. Thus, advocates of the 'skill' approach assumed that there were a number of 'parallel systems', each capable of dealing with a particular message more or less independently of other messages, a position very similar to that initially proposed by Allport, Antonis and Reynolds (1972).

With a measure of doubt about the single-channel hypothesis and limited capacity, psychologists began to look to alternative information processing models for an explanation of central intermittency. Rather than simply recognising the limitations of these theories, there appeared to be an underlying belief that serial processing models generally were incorrect and therefore further study would add little to the field of cognitive psychology (Kahneman, 1973). By 1975, the direction of psychological research shifted away from serial processing models, toward a detailed study of the increasingly popular multi-channel models. The issues surrounding multi-channel models will be taken up in the next section.

1.8 Resource theory

An important distinction between the major information processing theories was highlighted by Kahneman (1973). He argued that basically there have been two theoretical approaches to the analysis of attention; one set of theories emphasizes structural limitations to the mental system, and the other emphasizes capacity limitations. According to Kahneman, ". . . both types of theories predict that concurrent activities will be mutually interfering, but they ascribe the interference to different causes" (p. 11). He suggested that interference in structural models arises when two incompatible tasks require access to the same processing mechanism at the same time. In contrast, interference in capacity models arises when the capacity available is insufficient to satisfy the demand of the concurrent tasks. Thus, interference that occurs in structural models is specific and depends primarily on the degree to which competing tasks require access to the same processing mechanism. On the other hand, it is assumed that interference arising in capacity models is nonspecific, in the sense that it depends only on the demands of each task.

Initial attempts to reconcile the reanalysis of PSP data (Kahneman, 1973; Karlin & Kestenbaum, 1968) and the results of detection paradigm studies (Eriksen & Spencer, 1969; Shiffrin & Gardner, 1972) with limited capacity single-channel theories primarily involved modifications to the assumptions about the processing mechanism to allow some form of parallel processing.

Two different modification were proposed; either to the capacity of the system in the case of capacity theories; or alternatively, to the structure of the single-channel mechanism in the case of structural theories (Kerr, 1973).

The first proposal assumed that *capacity* is limited; interference between two tasks occurs only when the total capacity demanded by the combined tasks exceeds the system limits (Kerr, 1973). The model of attention proposed by Moray (1967), which we have already discussed, is typical of this approach. Moray accepted that capacity is limited but suggested that the concept of limited capacity should be viewed as a central processor which receives, transforms and generates messages, rather than a mechanism which passively carries or transmits messages. Further, he asserted that *". . . the functions performed on the messages themselves take up the capacity of the transmission system"* (p. 87). Thus, while the overall capacity of the processor is limited, the mechanism can divide up the available processing capacity and allocate it according to the demands of the task. In other words, the difficulty of the task determines how much capacity is allocated.

The second theory (Posner & Keele, 1970) proposed that only a limited number of the mental operations that occur during the performance of a complex task require processing space in a single-channel mechanism. A large proportion of mental operations are assumed to be processed in parallel, but at some stage the data must converge on a limited capacity single-channel. Thus, the *shortened* single-channel mechanism is effectively the cause of the central bottleneck. However, there have been differences of opinion about the location of the central bottleneck and the mental operations that must be processed through the single-channel. Some protagonists of the single-channel theory, for example, have suggested that the only process requiring the central mechanism is the response phase (Deutsch & Deutsch, 1963;

Norman, 1968), while others have suggested that other processes, such as memory retrieval (Posner & Snyder, 1975) or data transformation (Keele, 1973; Posner & Keele, 1970) also require the central mechanism.

Nevertheless, the predominant view of limited capacity models has assumed that capacity resides in a single undifferentiated reservoir and could be allocated in graded quantities to tasks as required. But it was noted that the capacity of a system was affected by a number of other factors such as memory stores, communication channels and peripheral sensory mechanisms (Kahneman, 1973), as well as psychological factors that interact with the system. As indicated in an earlier section, Kahneman labelled the psychological factor(s) involved in this process *psychological* or *mental effort*.

A succinct statement about the nature of psychological resources was provided by Norman and Bobrow (1975). They noted that, like capacity, processing resources are always limited. They suggested that when several processes compete for the same resource, eventually there will be a deterioration in performance. Moreover, when human processes become overloaded there is often a smooth degradation of task performance, rather than a *calamitous failure*, a feature of performance they termed the *principle of graceful degradation*. However, they suggested that under normal circumstances, functioning was characterized by a different principle, *the principle of continually available output*. They argued that ". . . processes must continually provide outputs over a wide range of resource allocation, even when their analyses have not yet been completed" (Norman & Bobrow, 1975, p. 45). Norman and Bobrow defined a process as a set of programs that are executed for a common purpose and for which resources are being allocated as a unit. Further, they considered resources to be mechanisms such as ". . . the various forms of memory capacity, and communication channels" (p. 45) as well as *processing effort*.

Norman and Bobrow maintained that the outcome of a process depends not only on the amount of resources invested, but also on the nature of the data available to the process. They defined two types of processes to explain the performance of complex tasks; those that are resource limited and those that are data limited. Resource limited processes are typically responsive to the amount of resources available to the task. If too few resources are applied, performance is poor. As the amount of resources increases, there is a general improvement in performance. Thus, whenever an increase in the amount of resources improves performance, the task is said to be resource limited. On the other hand, the performance of certain tasks is limited, not by the amount of resources allocated to it, but by the quality of the data. The detection of a faint signal against a background of noise is a typical example of a data limited process. If the best available, most sensitive equipment is unable to differentiate a signal from background noise, the addition of resources will not have any further effect on the outcome of the process. Essentially, if performance is independent of the amount of resource applied, the process is said to be data limited.

The view of the human information system proposed by Norman and Bobrow (1975) was of particular interest to advocates of parallel processing, because it offered an alternative theoretical framework for the analysis of dual-task interference in terms of competition for scarce resources. Furthermore, by the beginning of the 1980s it was evident that a realistic view of the processing mechanism must take into account the interaction between internal factors, such as attention (or capacity), channels and memory stores, as well as a number of external or environmental factors, including the nature of the stimulus and the arousal of the performer.

An information processing model proposed by Navon and Gopher (1979) was the first attempt to incorporate a sophisticated version of the resource concept to explain human performance. They were quick to recognised the analogy between the economic concept of scarce resources and the notion of resource limited processes proposed by Norman and Bobrow (1975). Further, they argued that a theory of resource allocation drawn largely from the field of microeconomics provided a particularly useful framework for the analysis of dual-task performance.

The underlying assumption of Navon and Gopher's theory was that the human information processing system has available a finite amount of processing facilities (or resources) that it uses to produce *processing output*. A resource can be broadly defined as any internal input essential for processing (e.g. locations in storage, communication channels etc.) that is available in quantities that are limited at any point in time (Navon, 1984). Moreover, Navon and Gopher assumed that under normal circumstances, the performance of a task is directly related to the *mental input*; that is, the amount of resource units available to it. Thus, as the amount of resources invested in a task increases, performance improves. Furthermore, the amount of resources applied to a task (mental input per unit time) determines the processing output rate (processing output per unit time).

Nevertheless, Navon and Gopher accepted that the performance of any complex task is characterized by a number of factors other than resources; factors they described as subject-task parameters. According to Navon and Gopher, their concept of a subject-task parameter was similar to Norman and Bobrow's *data quality*. However, they considered their term more definitive than *data quality*, in that it included a broader range of parameters, such as those arising from the environment (e.g. signal-to-noise ratio) as well as permanent or changing properties of the performer (e.g. level of practice). Thus, subject-task parameters describe information processing in terms of many different variables. They suggested that these parameters are constraints imposed on the system by the task. Within the constraint, the system is free to mobilize its resources to perform tasks as required.

Navon and Gopher assumed that performance is determined not only by the amount of resources invested, but also by their efficiency. Thus, a measure of overall performance is obtained from the product of the amount of resources invested and the average contribution of a unit of resources, that is, the *average efficiency*. In accordance with microeconomic theory, they defined average efficiency as the average contribution of all units of mental (or processing) input invested. An increase in the quantity of resources applied produces an improvement in performance that equals the increase in resources multiplied by their *marginal efficiency*. Navon and Gopher (1980) defined marginal efficiency as the output gain resulting from the last unit of mental (or processing) input, essentially the same use of the concept as that found in microeconomics. Thus, performance can be viewed as a function of several arguments - the subject-task parameters that are imposed *on* the system *and* the resources that are controlled by it.

The demand for resources is assumed to be a function of the subject-task parameter as well as the level of performance the subject intends to achieve. Navon and Gopher (1979) suggested that a task demands more processing resources the more difficult it is and the higher the criteria for successful performance are. They suggested that the system will supply resources to meet the demand determined by the intended level of performance, to the extent

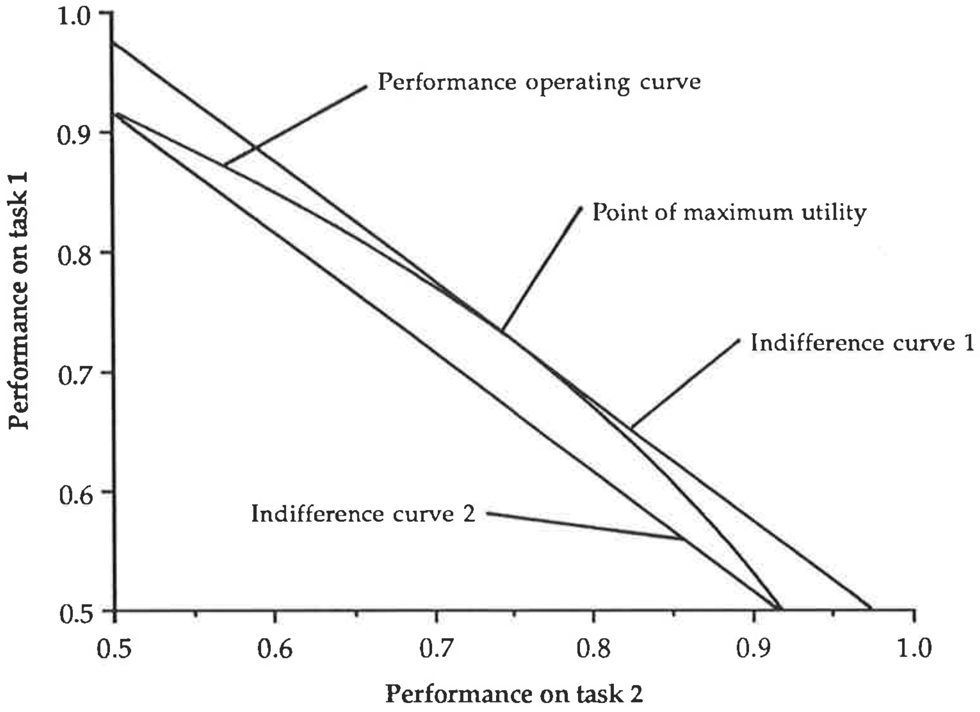


Figure 1.1 Hypothetical performance operating characteristic for a combination of two tasks. The amount of resources invested in each tasks is a function of the utility an operator gains from each task. Any level of performance within the area bounded by the vertical and horizontal axes and the performance operating (or resource boundary) curve is assumed to be feasible. However, levels of performance that lie outside this boundary are infeasible. The point of maximum utility is the optimal point for the performance of both tasks as determined by the individual's preferences and defined by the tangent of the performance operating curve and the indifference curve.

that they are available. In other words, supply equals either that demand *or* the limits of the available resources, whichever is the smaller.

Navon and Gopher indicated that analysis of cognitive performance becomes more complicated and interesting when two or more tasks must be dealt with simultaneously. They assumed that in this case both tasks apply demands to the same pool of resources. Further, the resources are supplied in proportion to their relative demands. However, Navon and Gopher also indicated that the marginal substitution of resources is such that performance of the combined tasks may not be equivalent to two single tasks. In other words, the substitution of a unit of resources from one task to another may not yield a gain in the performance of the second task equivalent to the gain that the same unit of resources would have on the first task. Thus, the performance of two combined tasks is a function of the subject-task parameters and resources allocated to each task; and the combination of the demand for resources for two tasks is a function of the subject-task parameters as well as the intended level of performance.

It is evident that within the capabilities of the system, and depending on the nature of the tasks, some levels of joint performance are feasible and some are not. Thus, if the amount of resources required to perform two tasks simultaneously is less than the total amount of resources available, then both tasks should be performed without interference. On the other hand, interference effects would be evident if the resources demanded by the two combined tasks exceeded the available resources of the system. This idea is reflected in a diagram known as the *performance operating characteristic* (Norman & Bobrow, 1975), whereby the boundary conditions for optimal performance of each task is graphically displayed (shown as Figure 1.1 on p. 46). The area northeast of the resource boundary line marks the infeasible region -

the region where the performance levels defined by the X and Y axes are unlikely to be achieved. Navon and Gopher suggested that when the supply of resources demanded by the operator cannot be met, a decision must be made as to the preferences amongst different mixtures of outputs for the two tasks. Those preferences can be represented by means of what economists term *indifference curves*. In this case, indifference curves define the various combinations of mental output to which the operator is indifferent.

According to a *normative model* proposed by Navon and Gopher (1979, 1980), resources will be allocated to optimize the operator's utility, a term used by microeconomists to describe the optimization of preferences. They suggested that the optimal mixture of resources will be the one that results in a joint performance associated with the highest utility. The value associated with the highest utility is the point at which the indifference curve is tangential to the resource boundary curve (see Figure 1.1). Navon and Gopher (1979) concluded that the adequacy of this model to describe performance is open to question, ". . . but if utility is considered at all by the processing system, then this model is probably not fatally wrong" (p. 219).

In a review of the theoretical conception of resources, Navon (1984) clarified a number of issues that originated from the initial work of Navon and Gopher (1979, 1980). Navon considered that while ". . . attention is a *phenomenal given* and *selection* is a fact; the premise of the existence of resources of limited quantity serving as mental input to processing is a theoretical claim that should be put to empirical test" (p. 217). Furthermore, he recognised that if the validity of *resource theory* was generally established, it would be an extremely valuable acquisition to cognitive psychology. Navon maintained that if dual-task interference could be proved to be the result of competition for scarce resources, and if the precise manner in which performance depends on the amount of resources available to the task could be determined, it would be possible to predict the combinations of levels of performance attainable when two tasks are time-shared. Thus, from a methodological point of view, the difficulty of various tasks as well as the similarity between processes could be assessed by their relative demands for resources. And from a theoretical point of view, ". . . the validation of resource theory would support the view that the limit on human information processing is an inherent property of the processing mechanism rather than a consequence of imperfections in software that can be amended with practice" (Navon, 1984, p. 217).

Navon (1984) suggested that resource theory provides a coherent framework for interpreting a number of empirical effects. For example, he suggested that the manipulation of task difficulty effects the processing output efficiency. On the other hand, the manipulation of task complexity may be used to alter the load imposed on resources to meet a performance criterion within a given time period. Similarly, the decrement associated with dual-task performance may be thought to impair the performance of the target task by limiting the amount of resources available to it. Navon (1984) suggested that ". . . a similar effect may be induced by varying the difficulty of the concurrent task, so that more difficult tasks consume more resources that could otherwise be devoted to the target task" (p. 219).

1.9 Overlapping tasks paradigm

In recent years there has been a revival of interest in the nature of the psychological refractory period largely through the work of Pashler and his colleagues (Pashler, 1984a; Pashler & Badgio, 1985; Pashler & Johnston, 1989). Briefly, Pashler was interested in the factors that influence dual-task interference. His initial studies set out to examine whether the PSP was the result of a general limit to processing capacity or whether some form of 'central bottleneck' restricts processing to one signal at a time. Further, if there was some kind of 'central bottleneck', what stage or stages of processing were affected by it? The experimental method used for Pashler's overlapping tasks studies was a modified version of the classical PSP task known as the locus of slack approach. Whereas PSP studies typically involved manipulating only the SOA between S_1 and S_2 and the number of choices of each signal, the locus of slack technique included a third variable - task complexity. Essentially, the locus of slack approach relies on manipulating stimulus factors to increase the duration of selected stages of processing.

According to the locus of slack logic, if a factor influences the duration of a stage at or beyond the bottleneck, factor effects will be additive with the effects of SOA. On the other hand, if a factor influences the duration of a stage prior to the bottleneck, factor effects will be underadditive with the effects of SOA (McCann & Johnston, 1992). Therefore, this approach provides a powerful method, not only for differentiating postponement (single-channel) models from capacity models, but also for distinguishing stages of processing that lie at or beyond the bottleneck from stages located prior to the bottleneck.

The results of Pashler's initial studies using this technique were interpreted as support for a postponement of processing of S_2 during the decision making stage. However, as Pashler pointed out, the data were 'strikingly' different from the predictions of several alternate models often considered to explain the PSP effect. These were the perceptual postponement, response-initiation postponement, and parallel capacity processing models. However, while the results of a subsequent study also using the locus of slack technique (Pashler & Johnston, 1989) were interpreted as being inconsistent with a general capacity sharing model, there was strong support for postponement of the response selection stage of processing.

To account for the results of these studies, Pashler (1989) proposed a two-component theory of divided attention. According to this theory, interference can arise in two ways; either from the *selection* of a response; or alternatively, from the perceptual stage of processing. Further, Pashler argued that it was the *selection* rather than the initiation of a response that must be carried out via a single mechanism; however, he indicated that the perceptual processing stage ". . . does involve something that amounts to a graded allocation of resources, rather than a discrete serial process" (p. 480).

A number of overlapping task studies were conducted to test the two-component theory. Pashler (1989) had subjects perform a variety of tasks involving speeded and nonspeeded responses to both visual and auditory signals. According to Pashler's theory, ". . . response selection to the first task postpones response selection in the second, but does not affect perceptual processing there" (p. 499). The results of these studies showed that when the first task involves a speeded auditory choice response, and the second tasks involves a nonspeeded complex visual task, increasing temporal overlap of the tasks does not substantially impair accuracy of the second response. This result was interpreted as providing broad support for Pashler's two-component theory of divided attention.

Pashler concluded that ". . . two separate and qualitatively different sorts of limitations constrain performance when people attempt to perform very simple tasks with visual stimuli presented at or near the same time. On the one hand, complex visual perceptual processes occur simultaneously, but they can generate mutual interference if their complexity reaches a certain level. On the other hand, central decision and response/selection operations cannot be performed simultaneously, and obligatory queuing occurs at this stage" (p. 507).

McCann and Johnston (1992) also tested some aspects of Pashler's two-component theory. They used a similar locus of slack technique to assess whether dual-task interference occurs before of after the response selection stage. They manipulated S-R compatibility for visual and auditory signals that varied both spatially and symbolically to test whether compatibility effects were additive or underadditive. Their results indicated that the effects of symbolic compatibility and task overlap were additive, but the effects of spatial compatibility and task overlap were underadditive. McCann and Johnston (1992) argued that this outcome provides strong evidence in favour of a bottleneck model of dual-task slowing in the overlapping tasks paradigm. Together with previous findings (Pashler, 1989; Pashler & Johnston, 1989) their results ". . . provide converging evidence that the bottleneck is central, somewhere between early stages of perceptual processing, such as stimulus encoding, and response initiation/execution" (p. 481).

1.10 Perceptual independence

Our discussion to this point has centred around a number of information processing models which have been proposed to account primarily for dual-task interference. Recall that dual-task interference arises when the processing of a signal from one task interferes with the concurrent processing of a signal from a second task. In other words, two tasks are said to interfere if the performance of one task *depends* on the presentation of the second task.

Conversely, if two concurrent tasks can be performed without mutual interference, they are considered to be perceptually independent. The idea of perceptual independence is a central issue in the study of dual-task interference.

A formal definition of independence has been proposed by Ashby and Townsend (1986). They suggested that signals A and B associated with two concurrent stimuli **A** and **B** are "... said to be independently perceived if the perception of each is in no way contingent or interacts with the perception of the other" (p. 154). The theoretical basis for the analysis of perceptual independence, derived from elementary probability theory, is the joint probability distribution function of the combined tasks. Essentially, the joint probability distribution defines the outcome expected if the performance of two concurrent tasks is statistically independent.

For example, consider a single experiment, and two events, A and B, with the associated probabilities $\mathbf{P}(A)$ and $\mathbf{P}(B)$ respectively. The conditional probability for events A and B is defined as;

$$\mathbf{P}(A/B) = \frac{\mathbf{P}(A \text{ and } B)}{\mathbf{P}(B)} \quad \text{if } \mathbf{P}(B) \neq 0 \qquad \ldots\ldots 1.$$

where $\mathbf{P}(A/B)$ is read: *the probability of A given B.*

The conditional probability assigns the probability of event A, given prior knowledge that event B has occurred. In the case where events A and B are independent, that is, where the outcome of event A has no effect on the outcome of event B;

$$\mathbf{P}(A/B) = \mathbf{P}(A) \qquad \ldots\ldots 2.$$

and from the definition of conditional probability,

$$\mathbf{P}(B/A) = \frac{\mathbf{P}(A \text{ and } B)\mathbf{P}(B)}{\mathbf{P}(A)} = \mathbf{P}(B) \qquad \ldots\ldots 3.$$

The definition of independence then follows;

Events A and B are independent if and only if

$$P(A \text{ and } B) = P(A)P(B)$$

A composite experiment composed of two independent discrete experiments X with outcomes ($x_1, x_2, x_3, \ldots x_k$) and Y with outcomes ($y_1, y_2, y_3, \ldots y_n$), has *kn* possible outcomes which may be listed as cells in a two-way table. If the probabilities associated with $P(x_i) = p_i$, and $Q(y_j) = q_j$ define the marginal probabilities, then the joint probability for each pair of events (x_i, y_j) may be obtained by multiplication of the marginal probabilities.

In the general case of the composite experiment consisting of two discrete random variables, X and Y, the composite model for the pair (X,Y) will incorporate independence if the joint probabilities are defined by multiplication of the marginal probability functions $f(x)$ and $f(y)$ such that:

$$f(x,y) = f_X(x) f_Y(y) \text{ for all } x,y.$$

From the definition above, it can be easily shown that if X and Y are independent, they have zero covariance, and it follows that they are pairwise uncorrelated.

A review of the theoretical issues involved in the study of perception by Garner and Morton (1969) outlined the relationship between perceptual and statistical independence. They argued that perceptual independence could be defined as either zero correlation, or performance parity. The definition of perceptual independence as zero correlation which they proposed followed the same statistical argument as that proposed above. Performance parity, however, was defined in a different form. Garner and Morton (1969) suggested that two perceptual processes can be considered independent if the performance of two perceptual tasks together is the same as the sum of the performances of the same two task when each is performed separately. Further, they indicated that the two tasks might involve the analysis of information in two modalities, or two subaspects of the same modality, or two dimensions of a set of stimuli.

Garner and Morton (1969) showed that performance parity and the concept of zero correlation are identical since they are related to each other through the same zero covariance criterion. The following example will help to clarify their point. Consider two random variables X and Y, whose sum of the variances $\Sigma(x+y) = \Sigma x + \Sigma y + 2r_{xy}\Sigma x\Sigma y$, the components making up the sum. It is clear from the formula that the variance of the sum ($\Sigma(x+y)$) equals the sum of the variances of the individual variables if and only if the correlation (r) between the variables is zero. Thus, the criterion for independence of two variables is the same for both definitions: zero correlation.

From our discussion, it is evident that the concept of perceptual independence is primarily concerned with perceptual processes; however, there are a number of other factors, such as the nature of the stimulus and the response and decision processes, that also have a significant effect on the operator's performance. The role that these factors take in the performance of perceptual tasks, as well as their relationship to perceptual independence, has been outlined in detail by Ashby and Townsend (1986). They provided a rigourous mathematical proof for perceptual independence in terms of statistical independence.

According to Ashby and Townsend, components A and B of a compound stimulus $\mathbf{A}_i\mathbf{B}_j$ are perceptually independent if the perceptual effects of A and B are statistically independent; that is, if and only if

$$f\mathbf{A}_i\mathbf{B}_j(x,y) = \mathbf{g}\mathbf{A}_i\mathbf{B}_j(x)\mathbf{g}\mathbf{A}_i\mathbf{B}_j(y)$$

for all x and y and where, for example, $\mathbf{g}\mathbf{A}_i\mathbf{B}_j(x)$ is the marginal distribution on dimension x when the stimulus is $\mathbf{A}_i\mathbf{B}_j$.

However, Ashby and Townsend indicated that a major difficulty involved in using a definition based on statistical independence to test empirically for perceptual independence is that in most experimental paradigms the distribution of perceptual effects is unobservable. To overcome this problem, two additional concepts, each related to perceptual independence, were proposed. The first is stimulus separability, the assumption that stimuli or stimulus components that act separately in the organism are therefore independent of each other. Ashby & Townsend (1986) argued that components A and B are perceptually separable if the perceptual effects of one component does not depend on the level of the other component; in other words, if

$$f\mathbf{A}_i\mathbf{B}_1(x) = f\mathbf{A}_i\mathbf{B}_2(x) \text{ for } i = 1, 2 \text{ and}$$

$$f\mathbf{A}_1\mathbf{B}_j(x) = f\mathbf{A}_2\mathbf{B}_j(x) \text{ for } i = 1, 2.$$

Similarly, the second concept assumes that components A and B are decisionally separable if the decision about one component does not depend on the level of the other. Ashby and Townsend (1986) concluded that under conditions where the components (A and B of stimulus $\mathbf{A}_i\mathbf{B}_j$) are normally distributed with equal means and the subject is responding optimally, stimulus separability and decisional separability imply perceptual independence. Consequently, both stimulus and decisional separability can be tested using the marginal probability distribution function derived for perceptual independence. Thus, the theory of perceptual independence outlined by Ashby and Townsend (1986) provides a framework for the evaluation of interference effects between concurrent tasks in a dual-task paradigm.

1.11 Summary

It is evident from this brief review of human information processing theory that one of the most important aspects of human cognitive behaviour to be explained is the performance of the operator under stress; typically, when the operator is required to perform two or more complex tasks at or near the limit of ability. Frequently, performance under such conditions diminishes significantly to a level well below that normally achieved when either task is attempted alone. This effect, generally known as dual-task interference, has been demonstrated in a variety of different ways. In RT studies, for example, the *temporal lag* often referred to as the *psychological refractory period* is attributed to the delay resulting from the presentation of a stimulus while the *central mechanism* is occupied processing a previous stimulus. On the other hand, the measure of performance used to demonstrate dual-task interference in the detection paradigm is based on the number of errors rather than the speed of performance. Studies using this method typically compare the response accuracy of each task when presented alone with the level of accuracy achieved when the same two tasks are performed simultaneously. Similarly, response accuracy is also used as a measure of the degree to which a secondary task is processed in dichotic listening studies. In this case, the subject's inability to recall the contents of a passage of prose presented during the shadowing of another passage is interpreted as evidence for dual-task interference.

To a large extent, the assumptions on which a particular information processing model is based are determined by the experimental paradigm that is used to demonstrate the interference effect. This is readily apparent from a consideration of Broadbent's limited capacity single-channel model. The results of the dichotic listening studies, on which Broadbent's model was originally based, indicated that a large proportion of the data received at the sensory level did not actually reach the processing stage. To account for this result, Broadbent incorporated a *switch* or *filter mechanism* which limited the amount of information reaching the processing stage. In contrast, Welford's single-channel model, which was heavily influenced by the results of RT studies, proposed a *temporary store* that is assumed to hold data until the central processing mechanism is free to accept them.

Although the assumptions about the processing mechanisms and the operation of each model are different, each model may be broadly categorized as belonging to either one of three basically distinct classes. Generally, models which have homogeneous assumptions tend to be categorized together in the same class. Models similar to the type proposed by Welford for instance, which have been grouped in a class known as structural models, ascribe dual-task interference to a *central bottleneck* which is an inherent feature of the processing mechanism. On the other hand, the second category of model, of which Moray's limited capacity model is typical, assumes that interference is the result of a limit to the amount of processing resources available to the performer. In contrast to both structural and limited capacity models, supporters of the third class of model, known as resource models argue that each structure or process has available its own specific capacity or resource that is primarily used to perform structure-specific or process-specific tasks.

Clearly, the assumptions on which each class of information processing model is based are extremely important, from a theoretical as well as a methodological point of view. The assumptions not only establish the basic characteristics of each class of model, but also the framework within which a particular model is evaluated. Furthermore, the outcome predicted for a specific experimental manipulation is largely determined by the basic characteristics of the model. Since each model is built around different assumptions, the predictions that each makes, about the effect that changes to the experimental task will have on the level of performance, are also different.

According to the single-channel hypothesis, for example, two stimuli presented so that they are both available for processing during the same period of time can only be processed one at a time. The signal from the second stimulus is assumed to be *held in store* and processed only after processing of the first stimulus is completed. The *temporal lag* or *delay* found in RT studies is a manifestation of this process. Welford (1952, 1959, 1967) argued that the mental operation responsible for the *temporal lag* is the decision process. He claimed that since each decision requires the exclusive use of the central processing mechanism, it is not possible to make two decisions simultaneously. Hence, Welford believed that understanding the operation of the central processing mechanism is crucial to understanding the concurrent processing of stimuli. Proponents of the single-channel hypothesis argue that the processing mechanism, when dealing with two concurrent tasks, functions in a similar manner to the *time sharing* operation of an electronic computer. Each signal, regardless of its level of complexity, must wait in turn for access to the central processing mechanism.

Although the manipulation of parameters such as the difficulty or complexity of the task will not directly effect the performance of the first (primary) stimulus, it will have an indirect effect on concurrent processing of the second stimulus. As the *degree of difficulty* or *complexity* increases, the central processing time required to make a decision increases. And as a result, the *trace* of the signal from the second stimulus must be held in store for a longer period of time, waiting for access to the central mechanism. Since the *trace* is known to degrade progressively over time, the longer it must be held in store, the more difficult it becomes to extract sufficient information to make an accurate decision about the stimulus. Hence, the information on which a decision about the second stimulus is made decreases as the decision time to the first stimulus increases. Therefore, the probability of a correct response to the second stimulus will diminish as the level of complexity or difficulty of the first stimulus increases. Furthermore, if the time required for the decision process to the first stimulus can be extended so that it is approximately equal to the time the *trace* of the second stimulus takes to degrade, the response to the second stimulus will be based on a minimal amount of information, with the probability of a correct response approaching chance level. However, the level of performance achieved for the task that has first access to the central processing mechanism should be largely unaffected by changing task parameters.

On the other hand, supporters of limited capacity theory argue that the central mechanism is capable of processing two stimuli simultaneously, provided there is sufficient capacity available to process both. Furthermore, the level of performance is assumed to increase monotonically with the amount of capacity invested (Kantowitz & Knight, 1978). Conversely, as the available capacity decreases, performance would be expected to deteriorate. When concurrent tasks place heavy demands for capacity on the central processing mechanism, dual-task interference is supposed to result. Moreover, if the demands for capacity exceed the available limit, the operator has the choice of at least two different strategies. One possible strategy would be to process one stimulus fully and as much of the second stimulus as possible with the *spare* capacity; the results expected would be optimum performance on the preferred task, but a significantly worse performance on the other (non-preferred) task. Alternatively, the operator could allocate equal amounts of capacity to each task. This would result in a diminished level of performance on both tasks. Clearly, the strategy adopted in each case would more or less depend on the instructions given to the operator. However, the overall level of performance achieved for concurrent tasks is also a function of task difficulty or complexity, since the amount of capacity demanded is assumed to depend on these parameters. More difficult tasks, for example, require the processing of more information per unit time (bits/sec). Therefore, while it may be possible to simultaneously perform two easy tasks which place little demands for capacity on the central processing mechanism, it is assumed that the concurrent performance of two difficult tasks is much more demanding and typically results in a performance decrement in either one or both tasks. Thus, the basic prediction of limited capacity models is an interaction between the level of performance and task difficulty (Kantowitz, 1985).

However, the predictions of models that postulate multiple capacity, such as resource models, are far more complex. Multiple capacity models are based on the assumption that resources are specific to each structure; in other words, each structure has its own processing capacity, namely, a resource, that is used primarily to perform structure specific functions. Resource theory ascribes variability in the performance of concurrent tasks to the amount of some limited internal input or resource dedicated to the task (Navon & Gopher, 1979). If we take a broad view of a resource as any internal input essential for processing (Navon 1984), it is clear that resources (such as transmission channels etc.) must be shared between processing mechanisms. However, for the purpose of the present study, a resource will be viewed in a more limited sense as an internal input required to process information actively - in other words, to analyse or transform data - rather than that required for passive processes such as transmission or storage. Thus, a resource will be considered as *processing capacity* that belongs to a specific structure, rather than being located in a single pool attached to the central mechanism as it is assumed by limited capacity theory.

If resources are truly *dedicated* to a particular structure and can only be used by that structure, the amount of resource available to each structure would be quite limited. The predictions of a multiple capacity model, assuming dedicated processing resources are not only more complex, but also clearly different from the predictions of either structural or limited capacity models. If two tasks require the same processing structure for example, they will also require access to the same dedicated resource. Therefore, the concurrent performance of both tasks will typically result in a deterioration in overall performance on both tasks. Moreover, the level of overall performance will decrease as the level of difficulty of either one or both tasks increases. In other words, a multiple capacity model predicts an interaction between the level of performance and task difficulty, a prediction similar to that of limited capacity models.

However, if two tasks do not require access to the same structural mechanism and therefore use different processing resources, the level of performance achieved when both tasks are attempted together would be approximately the same as the level of performance of either task alone. Furthermore, experimental manipulations which effect the difficulty of either task would have little effect on the performance of a second task. In other words, a resource model that assumes dedicated resources does not predict an interaction between the level of performance and task difficulty for tasks that involve different structural mechanisms.

Chapter 2

Visual backward masking: Limiting the apparent movement effect

2.1 The Dual-task paradigm

The purpose of this chapter is to outline a method for measuring visual perceptual performance at a level of accuracy sufficient to permit its application as a component in a dual-task. The basis for this work was a measure of sensory discrimination known as inspection time (IT).

Since 1823 when Bessel first proposed the *personal equation* to account for the differences between astronomers' observations of stellar transit times, numerous studies have investigated the operator's ability to concurrently process multiple sources of information. These studies have employed a variety of empirical methods. For instance, the method used for one of the first dual-task studies, known as the complication experiment (Boring, 1957), was based on essentially the same technique as that used by the early astronomers to time stellar events; similarly, Craik (1947, 1948) and Vince (1948) devised the pursuit tracking task to simulate the behaviour of operators involved in complex tasks such as aiming and tracking artillery at enemy aircraft. Around the same time, the concurrent processing of auditory information was examined at length by Cherry (1953), Broadbent (1952) and others using a dichotic listening technique. More recently, the detection method initially developed by Estes and Taylor (1964, 1965) has been used extensively by Eriksen and his co-workers (Eriksen, 1966; Eriksen & Collins, 1965, 1967; Eriksen & Lappin, 1965; Eriksen & Spencer, 1969) to investigate parallel processing of visual information. Additionally, a range of hybrid tasks, such as Allport, Antonis and Reynolds' (1972) combined piano playing-auditory shadowing tasks and Kantowitz and Knight's (1974) visual and tapping performance tasks have been used to investigate dual-task performance in different modes. As a consequence of the diversity of tasks used, the results of individual dual-task studies have varied greatly; essentially without any clear indication of what factors limit dual-task performance. However, it is evident from many of these studies that there are significant methodological and technical problems that make it difficult to determine the exact nature of the processes or mechanisms involved in cognitive performance.

2.2 *Individual differences*

Some of the difficulties arise from the wide variation in cognitive and perceptual abilities that are characteristic of the human population. These variations or *individual differences* in abilities, have been reported in a range of skills, from relatively simple measures of timed performance, such as estimates of reaction (Elithorn & Barnett, 1967) and inspection time (Nettelbeck, 1987), to more complex cognitive skills such as those involved in the assessment of intelligence (Eysenck, 1986). Individual differences are assumed to reflect the diverse social and cultural background of modern society as well as inherent biological variations of the human population. When developing a suitable method to investigate cognitive and perceptual processes, individual differences must be taken into consideration. Studies which use procedures that do not take these differences into account are liable to overlook the exact subtle variations in performance that are indicative of dual-task interference.

2.3 *Peripheral memory devices*

Another methodological issue that must be considered is the structure and operation of peripheral memory devices, namely, the *iconic* and *echoic* memories that are assumed to be part of the visual and auditory systems, respectively. The function of these two devices appears to be the same; that is, to hold an *image* of the stimulus for an extended period of time; sufficiently long to allow reliable processing. This feature of peripheral memory makes it particularly difficult to control precisely the time during which visual and auditory data typical of perceptual tasks can be accessed and used by the subject to make an accurate discriminative judgement.

Our theoretical understanding of iconic storage is largely due to the work of Sperling (1960) who showed conclusively that visual information can be *read* from iconic memory for some time after the physical stimulus has been removed. According to Sperling, the iconic store holds an extremely accurate image of the stimulation impinging upon the retina. Long (1980) argued that this image is precategorical or unprocessed, since all aspects of the original stimulus are present in storage. Moreover, Sperling's (1963) study indicated that the duration of iconic memory is brief (the order of 250 ms); the longevity being determined, to some extent, by the nature and luminance of the background and the adaptive state of the viewer's eye. Thus, information that is no longer available at the receptor level may still be retrieved and analysed through the central processor after the actual stimulus has disappeared.

While the existence of iconic memory is reasonably well established, the idea of echoic memory is very much a matter of conjecture. The rationale for echoic memory has been outlined by Neisser (1967). He argued that auditory information, in contrast to visual information, is typically spread over a period of time. Before it can be usefully analysed, it must be integrated into logical units. Therefore, the auditory processing system must have a medium available for temporary storage. Echoic memory is assumed to provide this function. Like its visual counterpart, echoic memory is thought to hold a retrievable image of an auditory stimulus for some time after the stimulus has ceased. Estimates of the time the image is available and can be retrieved vary from less than one second (Pollack, 1959) to as long as four seconds (Guttman & Julesz, 1963).

2.4 *Backward masking*

However, there is a relatively simple technique available that can control the time during which information can be read from these peripheral memory devices. The technique used, broadly referred to as *backward masking*, is thought to affect the contents of peripheral memory, rendering it *illegible* by erasing the image of the preceding target stimulus. Although several forms of *visual backward masking* have been used, like flashes of light or homogeneous patterned fields, the most effective technique appears to be a patterned stimulus that closely matches the contour of the target. This type of mask presentation is known as metacontrast (Alpern, 1952, 1953). Briefly, two theories have been proposed to explain the backward masking phenomenon. The interruption theory assumes that the application of a masking stimulus essentially replaces the representation of the target stimulus in the short-term visual store and therefore effectively reduces the target stimulus processing time to the interval between the target and mask. (This interval has been termed 'stimulus-onset-asynchrony', or SOA). On the other hand, integration theory assumes that backward masking is a result of the temporal integration of successive stimuli by the visual system. Thus, the representation of the target stimulus is degraded by overlapping contours of the target and mask.

Perception is assumed to be impaired by the degradation of the target stimulus, rather than by limiting the processing time.

The results of a number of studies investigating the nature of visual metacontrast have shown that the exposure of a stimulus is much more effective if the onset of the mask is delayed from 30 to 100 ms after the target stimulus is removed from view (Alpern, 1953; Averbach & Coriell, 1961; Weisstein & Haber, 1965). The delayed presentation of the masking stimulus appears to overwrite or interrupt the contents of peripheral memory, and is therefore evidence of an interruption theory. On the other hand, when the mask is presented at an interval of less than 30 ms after the target has been removed, it is apparently perceived as being simultaneous with the target, resulting in an integrated stimulus-mask combination that appears to be less effective as a masking device and from which information can still be gleaned.

A similar phenomenon has been shown to occur in audition. Thus, the properties of the preperceptual auditory store (the echoic memory store) may also be masked by a second sound of equal loudness presented shortly after the auditory target stimulus. This procedure is generally referred to as *auditory backward recognition masking*. Identification of the qualitative aspects of a target sound, such as its pitch or duration, is impaired if a second sound is presented within approximately 250 ms of the onset of the target tone (Hawkins & Presson, 1977; Kallman & Massaro, 1979). However, within the 250 ms range, accuracy of identification usually improves as the stimulus-onset-asynchrony (SOA) separating the two sounds increases. These results have been interpreted as indicating that it takes approximately 250 ms to read information from the echoic memory store; it has also been suggested that the results of auditory backward recognition masking experiments indicate that echoic storage has a duration of approximately 250 ms (Massaro, 1972, 1975).

2.5 *Practice effects*

A further methodological problem that has a significant effect on the outcome of perceptual studies is the effect that practice has on performance. It is well documented that the initial attainment of reasonable competence may take only a brief amount of practice (Welford, 1976). The author, for instance, has observed newly recruited trainee welders performing good quality welds after only a short explanation of the welding process and as little as 15 minutes practice, provided the welding equipment is correctly set and the pieces to be welded are of good fit and correctly aligned. But, at this stage of their training, any significant changes to either the task or the equipment invariably results in welds of much lower quality. However, following the initial period of training, further improvements in the trainee's welding skills usually require considerably more tuition and practice.

The results of a number of observations of people being trained have been compiled into a theory of complex skill training (Fitts, 1965). Fitts suggested that the acquisition of skill involves three different stages; the cognitive stage, the associative stage and the autonomous stage. During the cognitive stage, the performer is assumed to acquire some kind of basic understanding of the task and often seeks to develop an appropriate strategy that will help to simplify the task. Nevertheless, once an understanding of the basic skill is acquired and a suitable strategy developed, continued improvement in the performance of the skill is achieved only after an extended period of practice. This is assumed to occur during the associative stage and is characterized by increasing accuracy and speed of performance. By the autonomous stage, performance of the skill has been completely mastered. Once this has occurred, the skilled performer seems to have abundant time to do the same task with which the novice struggles.

Annett and Kay (1957) have argued that complete mastery of a skill is achieved when the input data in a repetitious task become highly predictable and hence carry less information. However, it may be that the performer, rather than focus on the overall task, has developed a specific technique or strategy that allows the skill to be executed reliably from a small portion of the data available. In other words, the performer has learned over a period of repeated practice that much of the data presented are invariant and therefore redundant. As such, they do not need to take up valuable processing resources dealing with redundant information. Hence, the performer learns through repetition to discriminate the task on the basis of a few, often quite subtle, but clearly important cues.

While practice effects can be largely overcome in industry, the situation in the experimental laboratory is rather different. This occurs because experiments can seldom be carried on for a sufficiently long period of time to assess whether a performer has completely mastered an experimental task (Welford, 1976). Frequently, the type of task selected and the level of performance accepted for an experiment is based on what it is reasonable to expect from participants, rather than what is ideal. In the final analysis, the closer the performer is to mastering an experimental task completely, the more reliable the results should be.

2.6 *Inspection time*

Although there are certain aspects of cognitive performance, particularly those involving the perceptual processing mechanism, that make the evaluation of dual-task performance difficult using traditional experimental methods such as reaction time, other measures of timed performance offer the possibility of more control over the experimental task. An index of perceptual processing, referred to as inspection time (IT), originally developed to estimate the speed of sensory processing within the framework of an accumulator or temporal summation model of decision processes (Vickers, 1970, 1979) may overcome some of the technical difficulties known to effect previous dual-task studies. IT has been defined as the time required for an observer to make a single inspection of sensory input on which a discrimination of relative magnitude is based (Vickers & Smith, 1986).

The IT task initially described by Vickers, Nettelbeck & Willson (1972) required the discrimination of the longer of two lines of markedly different lengths that were displayed for a brief period of time, the exposure being controlled by a backward masking stimulus. (Since that initial study most research has required that the subject locates the shorter line). Vickers *et al.* (1972) established the threshold value of IT as that exposure time required by the observer such that performance is virtually error-free. To account for momentary fluctuations in attention during the presentation of the target, virtually error-free performance was assumed to be that target exposure required for the observer to achieve, on average, 97.5% accuracy. However, since there are significant problems associated with estimation of IT at high levels of accuracy (Levy, 1992), a more reliable estimate of the time required to make a discriminative judgement can be obtained at lower levels of accuracy, for example, around the 80% level. This occurs predominantly because the slope of the cumulative normal frequency curve is a maximum around the 80% level but approaches zero at higher levels, such as 97.5%. Nevertheless, IT as defined at 97.5% accuracy, may be calculated by multiplying the estimate at 80% accuracy by the ratio of normal deviates defining the 97.5 and 80th percentile points under the normal curve (Nettelbeck, 1987). For the purposes of the present study, an estimate of speed of performance at an accuracy level of

85% will be used, but the range of values obtained can be converted to IT(97.5%) using the ratio method and checked against estimates obtained from previous studies if required.

There are several aspects of IT, and notably the IT procedure, that make it suitable for the analysis of dual-task performance, particularly where data are presented across two different modalities. For instance, a number of variants of the original tachistoscopic measure of IT have been developed, including an equivalent auditory version (Brand & Deary, 1985). Moreover, both the visual and auditory versions are reported to have extremely good test-retest performance reliability. Nettelbeck (1987), for example, surveyed a large number of studies in which test-retest correlations for repeated measures of IT were calculated. He concluded that the average test-retest correlation for the original (two line) IT task was of the order of 0.7, arguing that this result demonstrates IT provides a highly reliable index of some basic cognitive processing attribute. A test-retest correlation of similar magnitude has also been reported for a repeated measures analysis of an auditory version of IT (Raz, Willerman, Ingmundson & Hanlon, 1983).

The IT task also takes into account the different abilities of individuals to make discriminate judgements. Traditionally, IT has been used to demonstrate individual differences in perceptual performance. For example, there has been a great deal of work done to quantify the relationship between IQ and IT. The results of this work have consistently indicated a correlation of around -0.5 between these two variables (Kranzler & Jensen, 1989; Nettelbeck, 1982, 1987). However, since IT equates the performance of all individuals at a predetermined level of accuracy, it is also a useful method to control for individual differences in abilities. Thus, in practice, more capable individuals are able to make the required discriminative judgement on the basis of a shorter exposure of the target stimulus, while those less capable will require a longer exposure to achieve the same level of accuracy.

Another important feature of IT that makes it a particularly useful tool for the analysis of perceptual processing is its simplicity. Subjects can be familiarized with the discrimination task in a few minutes; subsequently, reasonable levels of performance can be achieved after as little as 50 practice trials. Moreover, reliable estimates of IT have been obtained using a computer-controlled version of the method of limits, in particular, an adaptive staircase technique which generates an estimate of IT quickly and efficiently, often in less than 100 trials. A second commonly used psychophysical procedure, known as the method of constant stimuli, which incorporates a fixed number of trials at each of several target exposure durations, may also be used to validate the reliability of the adaptive staircase method.

The influence of the peripheral or precategorical memory store is assumed to be controlled by a backward masking procedure which is intended to limit the exposure of the target stimulus. Typically, the tachistoscopic (two line) version of IT employs a pi-figure mask that matches the contour of the target stimulus. Tones (Kallman & Massaro, 1983), white noise (Bennett, Parasuraman, Howard & O'Toole, 1984; Brand & Deary, 1985), or a combination of both of these (Edwards, 1984) have been used as a backward masking medium for the auditory version of IT.

But although the backward masking stimulus is quite effective in controlling the duration of the image in perceptual memory, it does not necessarily limit the perceptivity of the target. Frequently, skilled operators are able to perform tasks using specific information about the target and mask display, rather than actually perceiving the target. The techniques used are broadly known as cognitive strategies.

2.7 *Cognitive strategies*

Not surprisingly, the diversity of opinion about the nature and development of strategies is considerable, perhaps as a result of the complex character of human behaviour. The general idea of a strategy is based on the supposition that many tasks can be successfully completed in a number of different ways (Young, 1978). Moreover, it has been suggested that the rules which govern such activities are 'man made' (Wood, 1978). The term strategy has been defined as an habitual way of selectively attending to and organising information into meaningful categories (Mischel, 1977).

In an interesting review of the strategy concept, Baron (1978) suggested an association between strategy development and intelligence. In particular, he proposed one important feature of intelligent behaviour was the tendency for the individual to simplify and organize the environment by developing cognitive strategies. Moreover, according to Baron, two additional factors, each inter-related with intelligence, effect the efficiency with which an individual uses a strategy. The first of these, which Baron labelled proficiency, is concerned with the degree of skill of the individual and assumed to be strongly influenced by practice. The second factor, capacity, is supposed to be an inherent human characteristic and therefore not ordinarily manipulated by psychological methods.

The position adopted by other investigators, notably Wood (1978), is in marked contrast to that expressed by Baron. Rather than implicating intelligence as the critical variable, Wood has suggested a strategy serves as a useful construct ". . . mediating the relationship between cultural and education factors on the one hand and mature, directed thinking on the other" (p. 353). Hence, in Wood's view, the factors which have a major influence on the development of a strategy are to a large extent learned rather than inherent, and therefore can be described as 'man made'.

Discrimination tasks are also frequently solved using some form of strategy. One study, for example, reported that as many as 50% of subjects typically use a strategy to perform the IT task (Mackenzie & Bingham, 1985). The results of previous studies indicate that one technique in particular, was the most effective and also the most frequently used. This technique has been termed the 'apparent movement effect'. Essentially, at the onset of the masking stimulus the subject perceives an apparent movement or flash as the mask replaces the target. Moreover, the apparent movement is distinctly more perceptible on the side of the target with the shorter line. Therefore, it seems clear that the apparent movement strategy occurs as a result of the backward masking procedure generally used to obtain an estimate of IT.

Recent studies investigating the association between IT, IQ and strategy development have produced some interesting results. Mackenzie and Bingham (1985) for example, found that when a group of subjects was divided on the basis of a questionnaire into strategy users and nonusers, the relationship between IQ and IT for users disappeared. But, for the nonuser group, the correlation remained highly significant, accounting for a large proportion of the variance.

However, while there was clearly a significant relationship between IQ and IT when subjects were selected from the nonuser group, Mackenzie and Cumming (1986) failed to find a significant difference between the two groups for either IQ scores, or estimates of IT. The implication of these studies is that although one group is more adept at developing and using strategies, the use of the strategy does not, at least from the evidence currently available, appear to improve significantly the performance of those subjects over and above that of the nonusers. Moreover, the results obtained by Mackenzie and his associates (Mackenzie & Bingham, 1985; Mackenzie & Cumming, 1986) pose some interesting questions within the context of the models proposed by Baron (1978) and Wood (1978).

For example, the results of Mackenzie's studies appear to be incompatible with the strategy concept proposed by Baron (1978) for at least two reasons. Firstly, it is clear that the intellectual ability of the subject, as measured by IQ tests, was not the major variable underlying the development of the apparent movement strategy, since Mackenzie's studies failed to find any difference between the strategy user and nonuser groups for IQ score. Moreover, the distributions of IQ scores for each group were very similar, reflected in the standard deviations, suggesting that these subjects were a homogeneous group with respect to IQ. Secondly, the lack of association between IT and IQ score for the apparent movement strategy indicates that IQ does not effect the proficiency with which a strategy is used. These results are consistent with the suggestion that there is an inherent propensity for subjects to use strategies for these tasks.

However, it should be stressed that the subjects participating in Mackenzie's studies were from a selected group; consequently the range of scores both for IQ and IT was quite limited and may have obscured any correlation effect between these two variables. Furthermore, for this particular task, the nature of the strategy may have resulted in a concentration of IT scores at a short but finite exposure duration for the strategy user group. There is some evidence to support this view in Table 2.1 of the Mackenzie and Cumming (1986) study. The reported variance for IT for the cue user group was significantly less than for nonusers ($p < 0.01$), although a significant difference in the estimate of IT between the groups was not found.

In the same study, Mackenzie and Cumming (1986) also investigated the effect of culture on IT scores. The motivation for this phase of the investigation was to test the Brand and Deary (1982) claim that IT is a culture-fair measure of 'g' and therefore previous experience and skills are not relevant to task performance. Mackenzie and Cumming (1986) argued that since video games involve essentially the same set of skills as those required for the IT task, a comparison of IT scores of video game players and non-players would test the cultural effect. The results which Mackenzie and Cumming obtained from this section of the study, however, failed to demonstrate a significant difference between the group of video game players and non-players. This finding was consistent with the position previously reported in Brand and Deary (1982). Nevertheless, the result of Mackenzie and Cumming's test of the cultural effect does not seem compatible with the strategy model suggested by Wood (1978). According to Wood's theory, Mackenzie and Cumming should have expected to find a correlation between culture and strategy. However, their result indicated convincingly that experience with video games did not give the player an advantage over the non-player.

If IT is to be usefully employed for the study of dual-task performance, it must reflect the processing time actually required for target discrimination. However, where strategies such as the apparent movement effect are used, the estimate obtained is likely to measure the minimum time in which subjects can perceive artificially contrived features of the target associated more with the masking procedure than the target - and these will enable subjects to make accurate discriminations without necessarily perceiving the target at all. This chapter therefore reports the outcome of two experiments designed to test whether a visual masking procedure can be developed that will eliminate the use of subtle features of the masking procedure, such as those provided by apparent movement or changes in brightness. This is particularly important because, if subjects are able to simplify the IT task by using a strategy based on information other than the relative line lengths of the target, the nature of the task changes. As the 'skill' required to use the strategy is 'mastered', the task becomes less demanding and, as a consequence, either less time or attention is needed for the discrimination. Faced with the problem of attempting to process two simultaneous sources of information, subjects are likely to adopt some form of strategy to simplify the task. If there is more than sufficient time available to complete either one of the tasks involved, the strategy chosen is likely to be based on time-sharing because this type of strategy would virtually eliminate the need to process both tasks at the same time. Thus, indices of perceptual performance that fail to control for the use of strategies are likely to invalidate the results of dual-task studies.

2.8 Experiment 1

The basic feature associated with the backward masking procedure seemingly responsible for the perceived apparent movement is an instantaneous flash clearly visible at mask onset. This feature, which can also be seen as small changes in brightness (Nettelbeck, 1982), is very pronounced and therefore more visible on the side of a two line target where the shorter line is located (see Figure 2.1). After taking part in IT studies, subjects often report that the flash or change in brightness associated with mask onset attracts the focus of attention.

Previous investigation of the apparent motion phenomenon has indicated that this effect is optimal for SOAs of 80 to 120 ms (Kahneman & Wolman, 1970). As it happens, subjects involved in IT studies are exposed to stimulus durations of around 80 to 100 ms in a high proportion of the practice and initial experimental trials which they attempt. Thus, it is possible that during the initial period of training, when stimulus durations are optimal to perceive apparent motion and subjects are given feedback about their performance, at least some subjects will acquire the basic skills to use the apparent movement strategy spontaneously.

Since the source of apparent movement lies with the usual masking procedure used supposedly to erase all traces of the target stimulus, an alternative masking process designed to conceal the flash may force subjects to respond as intended; that is, to discriminate the length of the target lines. A mask based on essentially the same technique as animated motion pictures, designed to simulate movement opposite to that at mask onset and thereby conceal the flash, can be expected to overcome the difficulties caused by the apparent movement effect.

In an attempt to overcome problems with the measurement of IT associated with the use of strategies, a two-stage masking technique was designed specifically to 'neutralize' the apparent movement. Basically, the masking process consisted of two different patterns presented in sequence. At the end of the target exposure, the first masking stage appeared for a period of 25 ms; it was followed by a second stage which lasted for approximately 325 ms. The rationale behind the mask layout was to induce a perceived movement or rotation of the masking figure in the direction opposite to that typical of the apparent movement. It was assumed that the apparent motion perceived at the second stage (25 ms after the offset of the mask) would help conceal the apparent movement at target offset and thereby make it more difficult for the subject to develop a clear association between the flash and the target configuration. The effectiveness of this two-stage masking procedure was compared with the traditional pi-figure mask in Experiment 1.

Method.

Subjects.

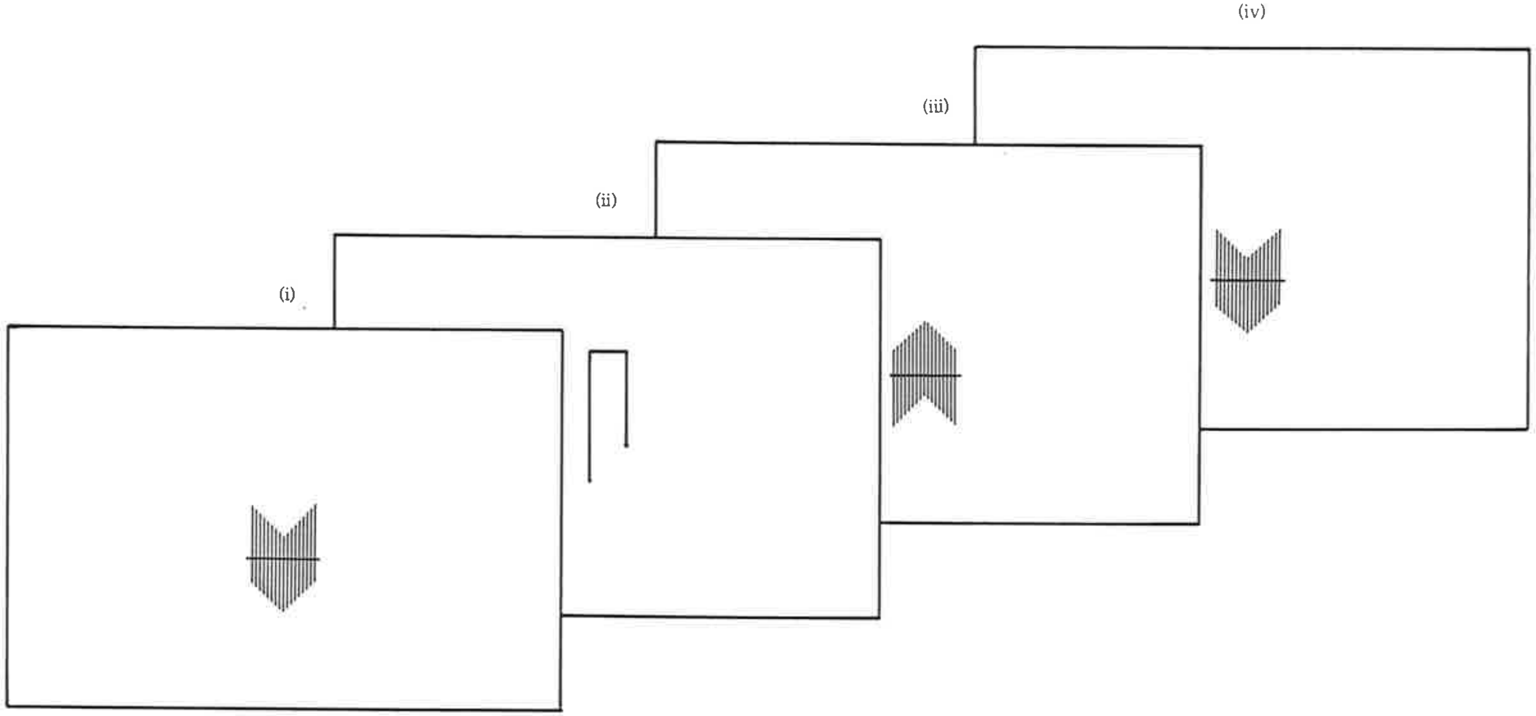
Fourteen University of Adelaide students (3 males, 11 females) enrolled in the first-year Psychology course volunteered to take part in this study. Of the original 14 volunteers, 2 males failed to complete the second part of the experiment and were therefore excluded from the final analysis. The ages of the remaining 12 participants ranged from 17 to 44 years (mean = 23, SD = 13). Each subject attended two experimental sessions one week apart. The first session required about one hour to complete; the second generally took less than forty minutes. At the outset, all subjects were tested for visual acuity using a Snellen Eye Chart; all were found to have normal, or corrected to normal vision. Before participating in this study, subjects were naive about the aims of the experiment.

Apparatus.

Stimuli were displayed using a Gerbrands G-1130 3-field tachistoscope converted in-house to four fields using standard equipment supplied by Gerbrands. All four fields were used to present a preliminary cue, a target (two alternatives in separate fields) and the masking figure. The luminance level for the four fields was uniform, set at approximately 6 cd/m^2. The timing for each field was via a modified Series 300 digital timer and the stimulus sequences were controlled by a (parameter estimation by sequential testing) computer algorithm known as PEST (Taylor & Creelman, 1967) run on an Intertec Super Brain computer.

Figure 2.1.

The sequence of stimuli used for the two-stage masking procedure, consisting of a cue figure (i); a target stimulus (ii); the first stage masking stimulus (iii); with the initial cue reappearing as the second stage mask (iv).



Stimuli.

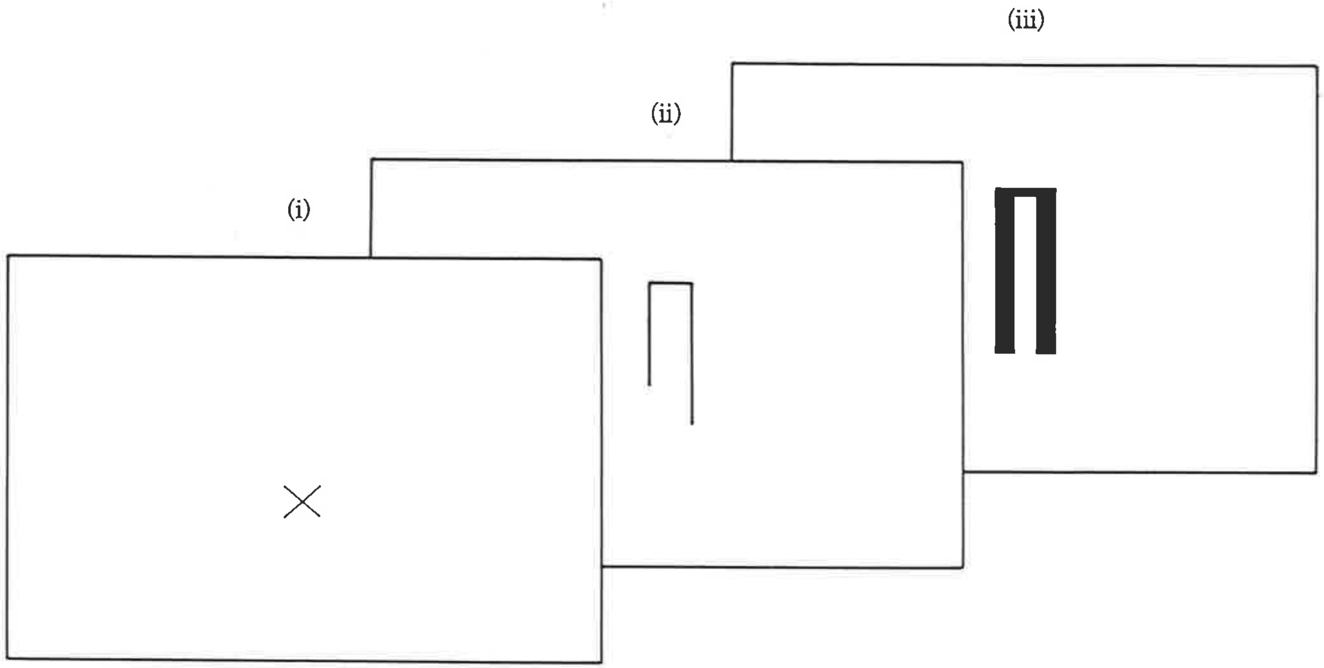
Each target stimulus consisted of two vertical lines 25 and 35 mm in length, 10 mm apart and closed at the top by a short horizontal line, drawn on white 150 by 100 mm index cards in 1 mm thick black india ink. The 'left' stimulus with the short vertical line on the left hand side (see Figure 2.1). The 'right' stimulus was a mirror image of the left. Two masking techniques were used during the course of this experiment. The first, a new experimental procedure, consisted of the two-stage masking sequence shown in Figure 2.1. The second masking procedure, the traditional pi-figure mask typically used to obtain tachistoscopic estimates of IT, provided the control. This procedure is shown in Figure 2.2. The viewing distance for all stimulus material was fixed at 80 cm.

Procedure.

Subjects were assigned to either one of two conditions for order of presentation when they first signed up for the experiment. In condition 1, session 1, each trial consisted of the presentation of a cue (1000 ms), a target stimulus (25 ms) and a backward mask (350 ms) as shown in Figure 2.2 Between the presentation of the target and mask, the screen was in total darkness for a variable period of time depending on the performance of the subject. The timing between the conclusion of the response to the previous trial and the initiation of the next was 2000 ms. The procedure for the condition 1, session 2 was essentially the same as that for session 1, but, with the traditional pi-figure masking procedure replaced by the two-stage mask shown in Figure 2.1. The timing of each trial for this mask consisted of the presentation of a cue (1000 ms), a target stimulus (25 ms), the first stage backward mask (25 ms) and the second stage backward mask (325 ms). For condition 2, the order of presentation for mask was the reverse of the order of

Figure 2.2.

The sequence of stimuli used for the pi-figure masking procedure, consisting of a cue figure (i); a target stimulus (ii); and the pi-figure masking stimulus (iii).



presentation for condition 1. The subject responded to the shorter line by depressing one of two buttons on a response key panel located adjacent to the subject at the base of the tachistoscope.

At the start of the first session, each subject was shown the experimental equipment and given a brief overview of its function. The task required for the condition to which the subject was first assigned was explained. With the aid of a duplicate set of stimulus cards, the subject was given an indication of the sequence of events to expect during the course of the experiment. It was explained that the subject should respond only to the short line of the target stimulus. Following this, the procedure for recording right and left responses was demonstrated. It was also emphasized that performance accuracy, rather than speed, was the most important criterion for this study. Each subject was given a series of practice trials prior to each experimental block until familiar with the task and the response required. The stimulus duration for all practice trials was set at 25 ms, and consisted of 10 trials at an ISI of 250 ms, 10 trials at an ISI of 150 ms, 20 trials at an ISI of 100 ms and 20 trials at an ISI of 50 ms. All subjects were required to achieve 100% accuracy at an ISI of 150 ms before continuing with further practice at shorter exposure durations and the experimental trials.

Immediately following practice, the subject completed a block of trials controlled by the PEST algorithm (Taylor & Creelman, 1967), which is designed to estimate the exposure duration at which the subject could respond with a predetermined degree of accuracy. For this experiment, the level of accuracy was set at 85% correct responses.

Table 2.1.

Means and SDs for measures of IT(ms at 85% correct) for two masking conditions and orders of presentation.

	Order of presentation					
	pi-figure - two stage mask			two-stage - pi-figure mask		
Mask	mean	SD	n	mean	SD	n
two-stage	36.6	18.1	7	49.4	28.7	5
pi-figure	52.9	19.2	7	64.4	20.7	5

Results.

The difference between measures of IT for two conditions and two orders of presentation was tested using a 2 x 2 factorial analysis. Means and SDs for IT for each of these conditions are set out in Table 2.1.

Because the number of replications per cell were unequal, the estimates of IT for each cell were averaged and tested using the method of means (Winer, 1971). The results indicated that the main effect for mask was not significant ($F = 3.11$; *d.f.* = 1,20; $p > 0.05$); similarly, the main effect for the order of presentation ($F = 1.88$; *d.f.* = 1,20; $p > 0.05$), and the order by mask interaction ($F = 0.01$; *d.f.* = 1,20; $p > 0.05$) were also both nonsignificant.

Since the order of presentation was not significant, the data were grouped and reanalysed, using a paired comparison 't' test (Snedecor & Cochran, 1978) to see whether there was a difference between the two masking procedures. The results indicated that the mean scores were significantly different, with the pi-figure mask clearly a more effective mask than the new two-stage procedure ('t' = 3.15; *d.f.* = 11; $p < 0.05$). Finally, the rank correlation coefficient (Spearman, 1904) calculated to establish the association between the measures of IT for each mask also proved to be nonsignificant ($\rho = 0.52$; *d.f.* = 11; $p > 0.05$).

Discussion.

This attempt to develop a more effective mask than the commonly used pi-figure mask was not successful. The results of this study clearly indicated that subjects were able to discriminate the target more accurately using the two-stage mask than the pi-figure mask. Moreover, since the mean IT (97.5%) scores for the pi-figure mask were consistent with the results of previous studies (e.g. see Nettelbeck, 1982, Tables 1, 2 & 3), it was evident from the estimates of IT obtained using the two-stage masking procedure, that this mask did not effectively control the amount of information available to the subject at target offset. Further, it is problematical whether the induced movement created by the two-stage mask was sufficient to neutralize the apparent movement effect, or whether it exacerbated it. However, it was clear this result was entirely opposite to the prediction that a dynamic mask which simulates apparent motion would overcome the difficulties associated with the backward masking procedure.

Nevertheless, the question of why the two-stage mask was less effective than the traditional pi-figure mask must be considered. Informal discussions with subjects after they had completed their involvement in the study indicated that one particular feature of the two-stage mask design was probably responsible for these results. Most of the subjects reported that they had adopted the strategy of using the horizontal line as a point of reference. They indicated that the use of this strategy seemed to simplify the discrimination task. In addition, it was suggested that the negative after-image of the target was evident after target offset, and this remained and tended to stand out against the grid lines of the mask.

It is possible the information exploited by subjects in the two-stage mask condition also involved perceived movement. Since the horizontal referent incorporated in the cue and mask design bisected the position of the ends of the target lines, at mask onset the longer line of the target commonly appeared to shrink up to the horizontal referent while the shorter line appeared to extend downward to it. Therefore, an efficient technique for the subject was simply to decide on which side the 'flash' above (or below) the horizontal referent occurred and to respond accordingly.

The degree of association found between the two measures of IT was no more than would be expected on the basis of chance. This outcome was in marked contrast to the findings of previous studies which have usually found significant correlations between repeated measures of IT (Nettelbeck, 1987).

2.9 *Experiment 2*

While the two-stage mask tested in Experiment 1 failed to overcome apparent movement problems associated with the IT procedure, the feedback received from those involved in the study did provide valuable information about the nature of the masking process. Information obtained from subjects after the test session indicated that the horizontal line, added to the mask in the absence of a fixation point, also provided subtle apparent movement cues similar to those reported for the pi-figure mask. Moreover, all subjects who reported using the horizontal line as a reference said that they found the discrimination with the two-stage mask easier. Thus, apparently, the horizontal line in the mask was, to a large extent, responsible for the perceived apparent movement.

It is evident from the pi-figure mask configuration that the square ends of the mask, which are adjacent to the critical area of the target, are the only horizontal feature that could be the source of the apparent movement cues. Several masks without horizontal lines or surfaces were designed and each one tested in a short pilot study to determine which was most the effective and hence worthy of further study. The final choice of mask is illustrated in Figure 2.3. On the basis of the subjects' reports about the persistence of the afterimage evident during the 'dark' interval between target offset and mask onset, the usual IT procedure, involving a fixation cue and with the target present for the full variable interval, was employed.

Although the primary aim of this study was to determine whether a new 'flash' mask could overcome the tendency for subjects to use a strategy based on apparent movement spontaneously, the reliability of the flash masking procedure when compared with the traditional one also warranted some consideration. The reliability of the traditional IT task (using the pi-figure mask) as a measure of perceptual speed is strengthened by a significant negative correlation with IQ (Nettelbeck, 1982, 1987). Therefore, to check that a similar estimate of perceptual speed was also being measured using the new 'flash' mask, IQ scores were obtained from most of those subjects involved in this study, and subsequently used to evaluate the correlations between both measures of IT and IQ.

Method.

Subjects

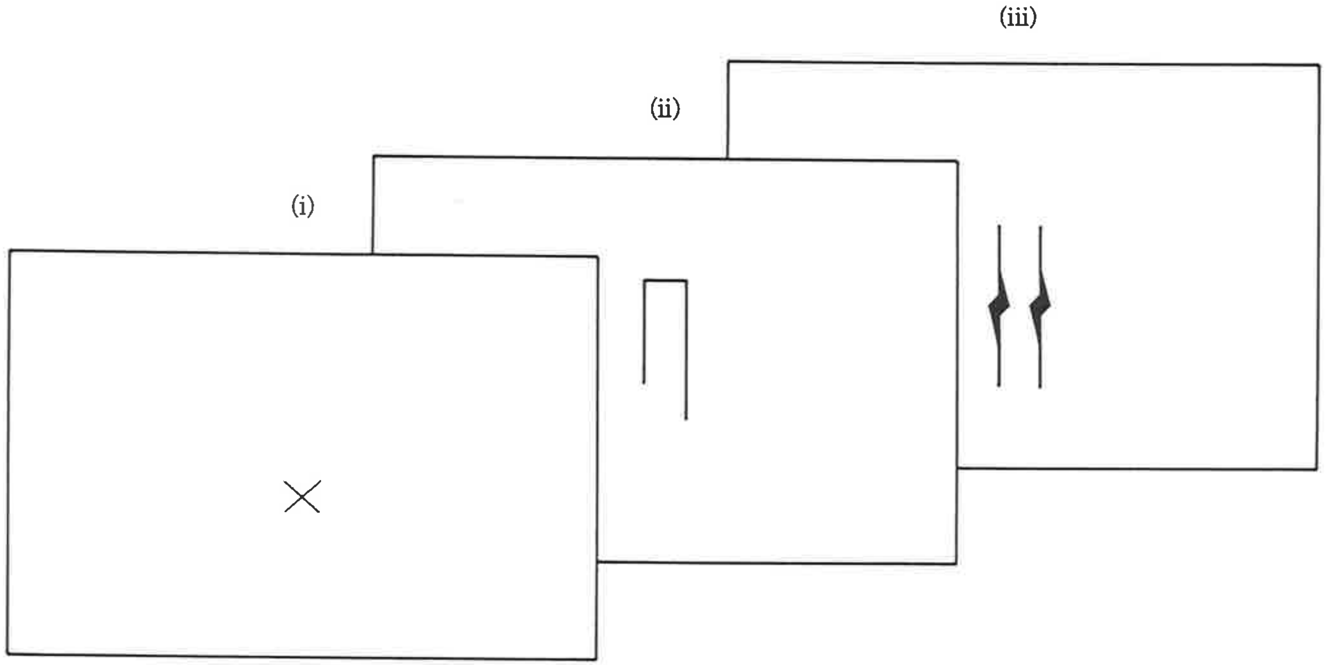
At the outset 20 undergraduate students (7 males, 13 females) enrolled in the first-year Psychology course at the University of Adelaide volunteered to take part in this study. One female was rejected from the sample after failing to meet the criterion of 85% correct responses at 100 ms. The ages of the remaining 19 participants ranged from 17 to 51 years (mean = 22, SD = 11). Two males completed the IT trials but failed to attend the IQ test session. For the remaining 17, Full Scale IQ (WAIS-R) ranged from 107 to 135 (mean = 119, SD = 9); Verbal IQ (VIQ) ranged from 107 to 141 (mean = 117, SD = 10) and PIQ ranged from 102 to 129 (mean = 116, SD = 8). All subject were tested for visual acuity and found to have normal or corrected to normal vision. All were naive about the aim of the experiment.

Apparatus

Stimuli were displayed using a Gerbrands G-1130 3-field tachistoscope, converted in-house to four fields. Luminance level for the four fields was uniform, and set at approximately 6 cd/m^2. The timing for each field was via a

Figure 2.3.

The sequence of stimuli used for the flash masking procedure, consisting of a cue figure (i); a target stimulus (ii); and the flash masking stimulus (iii).



modified Series 300 digital timer and the stimulus sequences were controlled by a version of PEST (Taylor & Creelman, 1967) run on a Intertec Super Brain computer. A response was made by pressing one of two buttons on a response panel located at the base of the tachistoscope.

Stimuli

The target stimulus consisted of two vertical lines 25 and 35 mm in length, 10 mm apart and closed at the top by a short horizontal line, drawn on white 150 by 100 mm index cards in 1 mm thick black india ink. The 'left' stimulus, had a short vertical line on the left side. The 'right' stimulus was a mirror image of the left. Two masking techniques were used; the first was the commonly used pattern overlay in the form of a pi-figure (see Figure 2.2); the second was the flash mask shown in Figure 2.3. The viewing distance for all stimulus material was fixed at 80 cm.

Procedure

Each trial consisted of the presentation of a cue (1000 ms) followed by a target stimulus presented for a variable interval and a backward mask (350 ms). The period between the conclusion of a response to the previous trial and the initiation of the next was 2000 ms. The procedure for condition 1 session 2 was essentially the same as that for session 1, but with the other masking procedure. For condition 2, the order of presentation for mask was reversed. For the IT task, each subject completed two sessions about one week apart, one for each version of the two masking procedures. Each session lasted about 45 minutes, half of which was taken up with practice. Order was approximately balanced across subjects. In the third session, which followed about a fortnight later, WAIS-R was completed.

At the start of the first session, the task requirements were carefully explained to each subject and, with the aid of a duplicate set of stimulus cards, the sequence of events that occurred within a trial was demonstrated. Instructions emphasized that accuracy rather than speed was the main consideration. It was stressed that responding was to the shorter line of the target, by pressing the appropriate button on the response panel. Initial practice involved a minimum of 40 introductory trials; 20 at 150 ms and 20 or more at 100 ms until 85% accuracy was achieved. This was followed by a further 10 practice trials at 75 ms to familiarize the subject with faster exposures. However, additional practice was given at any of these three exposures if the subject appeared to have difficulty with the task. This continued until it was evident that the subject was thoroughly familiar with both the task and its response requirements. In the test session, the initial exposure was at 125 ms, with the duration shortened for a series of correct responses but lengthened for errors, following the staircase algorithm PEST. The SOA required to achieve 85% correct responses was estimated by PEST based on eight reversals (where, for example, a change from shortening exposures to lengthening exposures constituted a reversal). On average, this required approximately 200 trials. The second session was essentially the same as the first with the same practice arrangements but, since subjects were already familiar with the task (other than the mask configuration), the introductory briefing was less detailed. At the completion of each session, subjects were asked to complete a short questionnaire about the way they had done the task and whether they had used any special technique that made the task easier; they were not specifically asked if an apparent movement strategy had been used.

Results.

IT data for two types of mask and two orders of presentation were analysed using a 2 x 2 factorial design. The analysis indicated that the main effect for

Table 2.2.

Means and SDs for measures of IT(ms at 85% correct) for two masks and orders of presentation.

	Order of presentation					
	pi-figure - flash mask			flash - pi-figure mask		
Mask	mean	SD	n	mean	SD	n
flash	90.7	26.4	10	92.3	23.3	9
pi-figure	70.7	27.2	10	74.9	16.5	9

mask was significant ($F = 7.91$; $d.f. = 1,34$; $p < 0.05$); but both the order of presentation and the mask x order interaction were not (F s < 1.0). Means and SDs for IT for each of these conditions are set out in Table 2.2.

Responses to the questionnaire administered following each experimental session were used to classify subjects as either 'cue users' (i.e. any recognizable strategy) or 'nonusers' for each type of mask. Analysis of the classification data using Fisher's Exact test indicated a significant difference in strategy use for each mask, irrespective of order of presentation ($p < 0.05$), with 10 subjects reporting use of cues for the pi-figure mask but only 3 reporting cues for the flash mask. Moreover, none of these three subjects reported specifically adopting a strategy based on apparent movement effects. Factorial analysis of the sample divided on the basis of strategy use confirmed a significant main effect for mask ($F = 10.55$; $d.f. = 1,34$; $p < 0.05$); however neither strategy use ($F = 1.39$; $d.f. = 1,34$; $p > 0.05$), nor the mask x strategy interaction ($F = 1.44$; $d.f. = 1,34$; $p > 0.05$) was significant.

For the full sample, performance under both masking procedures were highly correlated (Pearson $r = 0.72$; $d.f. = 17$; $p < 0.01$; two tailed) and there was a significant correlation between IT and PIQ, for both the pi-figure (Pearson $r = -0.61$; $d.f. = 15$; $p < 0.05$; two tailed) and the flash mask (Pearson $r = -0.65$; $d.f. = 15$; $p < 0.05$; two tailed), but not for VIQ (-0.24 and -0.21, respectively). This outcome held for nonusers (n = 15) with the flash mask ($r = -0.76$) but IT-PIQ correlations of -0.66 (n = 9 users) and -0.61 (n = 8 nonusers) were not significant for the pi-figure mask, because of the small samples involved. Full details of the IT-IQ correlations are given in Appendix 2.8.

Discussion

Analysis of IT data indicated that, while the two masking procedures were well-correlated, subjects required a significantly longer exposure of the target stimulus on average to achieve the same level of accuracy for the flash mask than for the pi-figure mask. The difference between the two estimates of IT with each mask was consistent regardless of the order of presentation, and SDs were about the same under both masking procedures. Since there was no significant interaction between mask and order, the difference between the two measures could not be attributed to practice effects. Furthermore, the results of subjects' responses to the questionnaire indicated that with the flash mask the likelihood of using a strategy based on apparent movement was far less than was the case when the pi-figure mask was used. Together, these results were consistent with the conclusion that the estimates of IT obtained using the flash mask were significantly less affected by the problem of strategies than were estimates of IT obtained using the pi-figure mask.

This conclusion was further supported by the correlations between IT and IQ found in this study which were very similar in both magnitude and sign to those reported in previous studies (Kranzler & Jensen, 1989; Nettelbeck, 1987) with significant correlations between IT and PIQ (-0.6); and small but negative correlations with VIQ. When the group was divided on the basis of strategy use into cue users and nonusers, the strength of the correlations remained essentially the same for the pi-figure mask, accounting for about 40% of the variance, although due to the small sample size this was not statistically significant. However, in the nonuser group the correlation was highly significant for estimates using the flash mask, accounting for approximately 55% of the variance (compared with 42% for the total sample in the same mask condition). Although further investigation is required to demonstrate the reliability and effectiveness of the flash mask conclusively, the results indicated that this flash mask generally diminishes the use of strategies, perhaps even eliminating the use of the apparent movement strategy altogether. The task developed therefore appeared to be ideal for the study of dual-task performance.

Chapter 3

Processing concurrent signals: A test of sequential vs. parallel processing models

3.1 *Introduction*

The aim of Experiment 3 was to investigate the nature of dual-task performance. Specifically, an attempt was made to identify whether the locus of dual-task interference is at a specific stage of perceptual processing; or whether such interference is the result of a general limit to the amount of information that can be processed in a given time. On the basis of data obtained from the study of central intermittency, Welford (1952) argued that the 'central bottleneck' evident in the processing of two successive signals is the result of the decision mechanism's inability to deal with more than one signal at a time. This argument formed the main premise of Welford's single-channel hypothesis. One the other hand, Broadbent (1958) interpreted the results of the dichotic listening studies as indicative of a more general limit to the amount of information that can be processed at any one time. This limited capacity aspect of the information processing system formed the central theme of Broadbent's model.

A significant problem arises when attempting to identify the locus of dual-task interference. Typically, information processing models are required to explain complex behaviour, often involving both cognitive and motor skill performance. As a consequence, the models are often intricate, comprising a number of processing operations or stages. This feature of the processing mechanism makes it extremely difficult to isolate a specific operational stage, which is necessary if the exact cause of the interference is to be determined. Problems of this nature occur with all multi-stage information processing models, including those proposed by Broadbent and Welford. However, the tasks selected for this study require a relatively 'easy' discrimination and hence can be described by a simple perceptual recognition model, similar to the general recognition model proposed by Ashby and Townsend (1986), but restricted to two observations per trial, each requiring a simple binary decision.

According to this model, the performance of simple perceptual tasks may be assumed to involve two internal stages of processing. During the first stage, a stimulus, which may be either visual, auditory or in some other sensory modality, is registered and transformed into some form of internal representation. In the second stage, the internal representation is used as the basis for a decision about which response to make. Clearly, the processing of information assumed to occur in a general recognition model is consistent with that required for a discriminative judgement task such as IT. Further, it is evident that if two discriminative judgement tasks are presented simultaneously in different sensory modes, any interference that results can only occur at the last stage of processing; that is, the decision and response stage (Treisman & Davies, 1973). Processing of decisions and responses are assumed to be higher order cognitive functions and therefore require access to the central processing mechanism. An independent decisions model (Shaw, 1982), developed from the theory of perceptual independence previously outlined in Chapter 2, may be used to assess the degree of interference between concurrent discrimination tasks.

3.2 *An Independent Decisions Model*

Consider an experiment in which signals S_x and S_y, from two independent tasks, x and y, are presented simultaneously. The target set for each signal consists of two elements $\{S_{x1}, S_{x2}\}$ and $\{S_{y1}, S_{y2}\}$. Let the probability of a correct response to signal S_x be $P(x)$; and the probability of an incorrect response be

$Q(x)$, where $Q(x) = 1 - P(x)$. Similarly, let the probability of a correct response to signal S_y be $P(y)$ and an incorrect response be $Q(y)$, where $Q(y) = 1 - P(y)$. Thus, in any given trial, one of four unique response patterns must be selected; either, correct responses to both S_x and S_y; a correct response of S_x, but an incorrect response of S_y and vice versa; or incorrect responses to both S_x and S_y. According to the basic model of statistical independence (of which decision independence is a special case), the probability distribution for each response pattern can be obtained from the marginal probability distribution for each signal. Thus, in terms of the number of correct responses;

$$\text{Probability (2 correct)} = P(x)P(y)$$

$$\text{Probability (1 correct)} = P(x)Q(y) + P(y)Q(x) = P(x)(1 - P(x)) + P(y)(1 - P(y))$$

$$\text{Probability (0 correct)} = Q(x)Q(y) = (1 - P(x))(1 - P(y))$$

To deal with information from simultaneous signals S_x and S_y, subjects can either process both signals concurrently, in other words, in parallel, or alternatively process each signal in sequence. If processing is in sequence, there are a number of possible strategies the subject can adopt. Either one signal can be processed completely before dealing with the other; or both may have alternate access to the processing mechanism and thus be processed in stages in a manner similar to the time-sharing operation of a computer.

Processing of simultaneous signals will be constrained by both internal (processing mechanism) and external (environmental) factors. The external factors, which are assumed to be under experimental control include the nature and timing of the experimental task, and the instructions given to subjects. Within the external constraints under experimental control, the operation of the processing mechanism may be inferred from analysis of the probability distribution function for S_x and S_y.

The basic assumption of a concurrent or parallel processing model is that two (or more) signals can be processed simultaneously and without interference. Assuming that the assigned level of single-task performance for both tasks is α, then;

$P(x) = P(y) = \alpha$; and $Q(x) = Q(y) = (1 - \alpha)$.

Therefore,

Probability (2 correct) $= \alpha^2$

Probability (1 correct) $= \alpha(1 - \alpha) + \alpha(1 - \alpha) = 2\alpha(1 - \alpha)$

Probability (0 correct) $= (1 - \alpha)^2$

On the other hand, the basic assumption of a strict sequential processing operation is that only one task can have access to the central processing mechanism at any given time. Moreover, if the timing and nature of these two events are well controlled so that it is difficult to gather information about the second task after the first has been processed, the probability of a correct response to the second event would be equal to chance level performance, that is, either $P(x) = 0.5$ or $P(y) = 0.5$. Assuming that the subject is biased toward task y, then;

$P(x) = 0.5$; $P(y) = \alpha$; $Q(x) = 0.5$; $Q(y) = 1 - \alpha$

Therefore,

Probability (2 correct) $= 0.5\alpha$

Probability (1 correct) $= 0.5\alpha + 0.5(1 - \alpha) = 0.5$

Probability (0 correct) $= 0.5\,(1 - \alpha)$

However, if the processing mechanism operates in a sequential manner, but the subject can 'time-share' the two tasks by switching attention from one task to the other, the probability distribution function defines the performance limits, rather than specific outcomes. Assuming that the subject processes S_x first and then switches attention to S_y and that the probability of a correct response to $S_y = \beta$ where $0.5 \leq \beta \leq \alpha$, then actual performance is more or less dependent on the time taken processing S_x, as well as on environmental factors such as the effectiveness of the backward masking procedure used to control S_y.

Thus,

$$\text{Probability (2 correct)} = \alpha\beta$$

$$\text{Probability (1 correct)} = \alpha(1-\beta) + \beta(1-\alpha)$$

$$\text{Probability (0 correct)} = (1-\alpha)(1-\beta)$$

If the α level is set at 0.85 the set of equations reduces to;

$$\text{Probability (2 correct)} = 0.85\beta$$

$$\text{Probability (1 correct)} = 0.85 - 0.7\beta$$

$$\text{Probability (0 correct)} = 0.15(1 - \beta)$$

Under each of these models, a least squares estimate of the probabilities associated with S_x and S_y may be obtained from the marginal totals of the 2 x 2 contingency table and used to test for goodness-of-fit.

While this type of model can effectively compare single task with dual-task performance, further information about the independence of two tasks - that is, whether the qualitative nature of each task remains unchanged in a dual task environment - can be obtained by observing the effect which changing the complexity or difficulty of either task has on performance (Kantowitz, 1985). Thus, while two simultaneous tasks may be reliably performed when both tasks are relatively easy, changing the complexity or difficulty of either one or both may result in a significant decline in performance of one or both tasks. This decline is assumed to imply dual-task interference, and may be interpreted as an indication that a common processing stage is involved (Treisman & Davies, 1973).

The independent decisions model may be easily tested using measures of visual and auditory discrimination. For example, single-task performance for each task may be obtained by first establishing the time required to discriminate a visual target (at a pre-determined level of accuracy) and then using this same timeframe to obtain an estimate of frequency discrimination at the same level of accuracy. The dual-task then simply involves the presentation of both signals within the same period of time.

3.3 *Experiment 3*

Method

Subjects

Sixteen undergraduate students (10 males, 6 females) enrolled in the first year Psychology course at the University of Adelaide were recruited to take part in this study. One male and one female were rejected from the sample after failing to meet the minimum performance criterion for the auditory task. The ages of the remaining 14 participants ranged from 17 to 33 years (mean = 21, SD = 11). At the beginning of the experimental session, subjects were tested for visual acuity using a Snellen Eye Chart. All were found to have normal, or corrected to normal vision. They were also asked if they had any specific hearing defects that would effect performance on a tone discrimination task. None of the subjects reported knowledge or history of any hearing problem. At the outset, all subjects were naive about the aim of the experiment.

Apparatus

Two experimental tasks were used in this study; one visual and the other auditory. Visual stimuli were displayed using a Gerbrands G-1130-3 field tachistoscope, converted in-house to four fields. Luminance level for the four fields was constant throughout the experimental trials, and set at approximately 6 cd/m^2. The auditory signals were pure sine waves with a frequency band in the range 900 to 1450 Hz produced by a signal generator which incorporated a programmable crystal oscillator. Tones were presented through Pioneer Model 8E-6 stereo headphones to both left and right ears. The timing of both visual and auditory stimuli was via a modified Series 300 digital timer, controlled by a North Star Advantage computer. Single task stimulus sequences for both tasks were controlled by the same version of PEST (Taylor & Creelman, 1967) as that used in Experiment 2. Dual-task stimuli were preprogrammed, timed through the same Series 300 digital timer under the control of the North Star computer. Visual responses were recorded by pressing one of two buttons located horizontally on the right side of a response panel. Two buttons, located vertically on the left-hand side of the same panel were used to record auditory responses.

Stimuli

The visual target stimulus consisted of two vertical lines 25 and 35 mm in length, 10 mm apart and closed at the top by a short horizontal line, drawn on white 150 by 100 mm index cards in 1 mm thick black india ink. The 'left' stimulus had a short vertical line on the left side; the 'right' stimulus was a mirror image of the left. The masking stimulus was the flash mask developed and tested in Experiment 2. The viewing distance for all stimulus material was fixed at 80 cm. The auditory discrimination task required subjects to identify one of two alternative target tones; either a 'high' tone (above 1200 Hz) or a 'low' tone (below 1200 Hz). Responses required were: Upper button in the vertical array for the high tone; and lower button for the low tone. For any trial, the target tone had an exposure duration equivalent to visual IT, but a variable frequency. Exposure of the target stimulus was terminated by the onset of a 1200 Hz backward recognition masking stimulus. The level of intensity for both the target and masking tone was set at 78 dB.

Procedure

Each subject completed three separate tasks during an experimental session that lasted approximately 75 minutes. The first task was a measure of visual IT. The second was an auditory tone discrimination task developed to provide an estimate of threshold discrimination within a timeframe equivalent to visual IT. This task will be referred to hereafter as the 'auditory tone discrimination' (ATD). Finally, subjects were required to perform both the visual IT and auditory discrimination (ATD) for the dual-task condition.

After giving a brief description of the two experimental tasks, the visual IT procedure was explained in detail. Each trial consisted of the presentation of an attentional cue (a small cross, appearing in a central location for 1000 ms) followed by a target stimulus presented for a variable interval, the processing of which was terminated by the application of a backward mask (350 ms). The period between the conclusion of a response to the previous trial and the initiation of the next was 2000 ms. The stimulus sequence was demonstrated using a duplicate set of cards. It was carefully explained that responding should be to the shorter line, and that accuracy, rather than speed, was the important performance criterion. The procedure for recording left and right responses was also demonstrated. Before attempting the visual experimental block, subjects were given sufficient practice so that they were familiar with the task. Practice consisted of a minimum of 20 trials at a stimulus duration of 150 ms and 20 trials at 100 ms, with further practice at either of these exposures if necessary, followed by 20 trials at 75 ms and 10 trials at 50 ms. All subjects were required to achieve 85% accuracy at 100 ms before continuing practice at faster exposures. Immediately following the last ten practice trials, an estimate of IT was obtained using the staircase algorithm PEST (Taylor & Creelman, 1967). The initial stimulus exposure for PEST was 100 ms, with the durations shortened for a series of correct responses, but lengthened for a series of incorrect responses. On average, 120 trials were required to achieve an estimate of IT at the 85% level.

At the completion of the visual task, subjects were briefed about the ATD, which was described as an auditory equivalent of visual IT. For the ATD, each trial consisted of the variable frequency target tone (with the exposure duration set identical to the subject's previously estimated visual IT), followed by a 1200 Hz backward recognition masking tone that lasted 350 ms. The frequency of 'high' and 'low' tones varied equally about the 1200 Hz masking tone. The minimum time between successive trials was 2000 ms. The auditory task was demonstrated using long bursts of tones; first, 1400 Hz followed by the 1200 Hz mask to demonstrate a 'high' frequency discrimination, and second, 1000 Hz followed by the 1200 Hz mask for the 'low' frequency discrimination. The procedure for recording both 'high' and 'low' responses was shown to the subject at the same time and, again, it was stressed that accuracy rather than speed was the performance criterion. Subjects were given considerable practice before attempting the experimental trials, a minimum of 20 trials at 100 ms duration with 150 Hz variation (i.e. 1200 ± 150) between the target and masking tones, 20 trials at 100 ms with 125 Hz variation, 20 trials at 75 ms with 100 Hz variation and a minimum of 10 further trials at the actual values set for the experimental block. Subjects were required to achieve 85% accuracy at 100 ms with 125 Hz variation before continuing with the final practice blocks. Following practice, an estimate of ATD was obtained using the same version of the PEST algorithm as for the visual task, to control frequency variation. This required approximately the same number of trials as the visual measure of IT. After finishing the ATD, subjects were given a short rest while the data obtained from the visual and auditory tasks were entered into a program for the dual-task condition.

Immediately after the rest period, instructions for the dual-task condition were explained in detail. There were two levels for the dual-task consisting of an introductory block of 'easy' trials and 3 blocks of 'difficult' trials. The procedure for both the 'easy' and 'difficult' conditions was essentially the same. The difficult visual task involved the presentation of the same cue, target stimulus and backward mask as that used to estimate visual IT, with the presentation of the target stimulus equal to the subject's IT calculated at 85% accuracy. Concurrent with the visual target, an auditory target tone was presented for the same period of time and followed by a 1200 Hz backward recognition masking stimulus, essentially the same as the ATD. The frequency difference between the target tone and the mask was the previously established level to which the subject could respond with 85% accuracy. Thus, for example, if the visual IT (at 85% accuracy) was 100 ms and the estimated ATD (at 100 ms duration) was 50 Hz, the difficult dual-task condition consisted of the concurrent presentation of a visual target stimulus (with the shorter line on the left or right) and either a 1250 Hz ('high') or 1150 Hz ('low') target tone for a 100 ms duration. Immediately following the target presentation, a visual (flash) mask and a 1200 Hz auditory mask were applied. The 'easy' task differed from the 'difficult' task only in the time during which the visual and auditory target stimuli were exposed. Following the procedure outlined by Nettelbeck (1987, Footnote 4), an estimate of the time required to achieve 90% accuracy was calculated by multiplying the IT value (85% accuracy) by the ratio of normal deviates defining the 90th and 85th percentiles under the normal curve. Using this method, the time for the 'easy' task (at 90% accuracy) was estimated to be 125% of the time required for 85% accuracy.

Subjects were told that the two stimuli, one visual and one auditory, identical to those used in the tasks they had just completed, would occur simultaneously. They were also told that both tasks were equally important, and that they should try to respond to both as accurately as possible. The dual-task was arranged in four block of 32 trials each, with the first block of trials being the 'easy' condition and the final three blocks, the 'difficult' condition. Between each block of trials, subjects were given a one minute rest. The responses for each trial were recorded by computer and, after the last trial of each block had been completed, compiled in a 2 x 2 matrix. At the completion of the fourth block, subjects were given a short questionnaire about the way in which they had performed both the single and dual-tasks.

Results

Estimates of visual IT at 85% accuracy, obtained in the single-task condition, using the flash mask, were consistent with those obtained in the previous experiment (mean = 93 ms, SD = 20). The average frequency discrimination, also at 85% accuracy, was 51 Hz (SD = 20). Dual-task data for each subject consisted of an array of four elements [**a**, **b**, **c**, **d**] with **a+b+c+d=n**, where **a** represents the number of trials in which subjects responded correctly to both the auditory and the visual task; **b**, the number of trials in which subjects responded correctly to the auditory, but not the visual task; **c**, the number of trials in which subjects responded correctly to the visual, but not the auditory task; and finally **d**, which represents the number of trials in which the responses to both tasks were incorrect. There were two arrays scored for each subject; one of **n** = 32 trials for the 'easy' condition and one of **n** = 96 trials for the 'difficult' condition.

The dual-task data were analysed in three ways; firstly, the data obtained in each condition, consisting of elements **a**, **b+c** and **d**, representing the number of trials with two correct responses, the number of trials with one correct response and the number of trials with no correct responses respectively, were tested for homogeneity. Secondly, the data from each condition were tested for conformance with the information processing models previously outlined. Finally, the proportion of correct auditory and visual responses resulting from the dual-task data, estimated from the elements in the array by $(\mathbf{a}+\mathbf{b})/\mathbf{n}$ and $(\mathbf{a}+\mathbf{c})/\mathbf{n}$, respectively, were compared with single task performance.

Analysis of the 'easy' and 'difficult' dual-task data indicated that neither set was homogeneous, with χ^2 values of 57.86 (d.f. = 26; $p < 0.01$) for the 'easy' condition and 143.72 (*d.f.* = 26; $p < 0.01$) for the 'difficult' condition. Since the data from each condition could not be collapsed into an array of three elements, the data from each subject for each condition were tested for goodness of fit using χ^2 analysis under the null hypothesis of no difference between single and dual-task performance as defined by the parallel processing model previously outlined. According to the predictions of this model $\mathbf{n}\alpha^2 = \mathbf{a}$, $\mathbf{n}\alpha(1 - \alpha) = \mathbf{b+c}$ and $\mathbf{n}(1- \alpha)^2 = \mathbf{c}$, where α denotes the established level of single-task performance.

The χ^2 values resulting from this analysis varied greatly, with the data from some subjects consistent with the parallel processing model, but the data from the others clearly not consistent with this model (see Appendix 3.3). It was evident from the analysis that the raw score data from each subject could be assigned to one of two distinct groups; the first consisting of subjects whose data were consistent with the parallel processing model; and the second consisting of those subjects whose data were not. In other words, in each condition subjects were subsequently assigned to one of two partitions, essentially on the basis of whether or not their data were consistent with the parallel processing model. Data were accepted as being consistent with the parallel processing model if the χ^2 value obtained from the goodness of fit of the data to the model had an associated probability of greater than 0.05. On the other hand, if the χ^2 value was so extreme that the probability of obtaining such a value by chance was less than 0.05, the data were considered not consistent with the parallel processing model. It proved to be the case, however, that the data not consistent with the parallel processing model were clearly defined by large χ^2 values and very low associated probabilities; in one of the 11 arrays (four from the easy and seven from the difficult condition) the associated probability was less than 0.02; in the remaining 10 arrays, the associated probabilities were all much less than 0.01. On the basis of the χ^2 goodness of fit results, the data of 10 subjects from the 'easy' condition and seven from the 'difficult' condition were consistent with the parallel processing model and therefore partitioned from the total sample.

The remaining data not consistent with the parallel processing model were analysed for goodness of fit to the single-channel model; that is, where $\mathbf{n}\alpha/2 = \mathbf{a}$, $\mathbf{n}/2 = \mathbf{b}+\mathbf{c}$ and $\mathbf{n}(1 - \alpha)/2 = \mathbf{c}$. The results indicated that the data from all four subjects in the easy condition and four of the seven subjects in the difficult condition were consistent with the single-channel model. Interestingly, the four subjects whose data were not consistent with the parallel processing model in the 'easy' condition were also among the seven whose data were not consistent with the parallel model in the 'difficult' condition. Subsequent analysis showed that the partitioned data consistent with the parallel processing model were homogeneous with χ^2 values of 18.27 (*d.f.* = 18; $p > 0.05$) and 15.65 (*d.f.* = 12; $p > 0.05$) for the easy and difficult conditions, respectively. The data that were not consistent with the parallel processing model from the easy condition were also homogeneous ($\chi^2 = 4.40$; *d.f.* = 6; $p > 0.05$); however, the data from the difficult condition were not ($\chi^2 = 71.02$; *d.f.* = 12; $p > 0.05$). A summary of the dual-task data and χ^2 analysis is given in Appendix 3.3.

The data partitioned from each condition for each subject were converted to percentages and modified using an *arcsin transformation* to stabilize the variance. Separate analysis of variance of the percentage of correct responses confirmed a significant condition effect for the auditory ($F = 11.81$; *d.f* = 1,24; $p < 0.01$) and visual task ($F = 7.39$; *d.f* = 1,24; $p < 0.05$). There was also a significant model effect for the visual task ($F = 5.04$; *d.f* = 1,24; $p < 0.05$), but not for the auditory task. Further, there was no significant condition by model interaction for either task ($p > 0.05$). A full summary of the Analysis of Variance is given in Appendices 3.5 and 3.6. A detailed comparison of the percentage of correct responses to visual and auditory stimuli for each partition highlighted the difference between the two groups. Subjects whose data were consistent with the parallel processing model typically performed the auditory task extremely accurately, with significantly greater than 90% correct responses (94.4%, $z = 2.61$, $p < 0.01$) for the 'easy' condition and significantly greater than 85% correct responses (89.6%, $z = 3.33$, $p < 0.01$) for the 'difficult' condition. However, while visual discrimination was consistent with the single-task performance level (89.1%, $z = 0.56$, $p > 0.05$) in the 'easy' condition, it deteriorated to be significantly worse than the predicted 85% accuracy in the 'difficult' condition (81.9%, $z = 2.29$, $p < 0.05$). On the other hand, the data that were not consistent with the parallel processing model showed a different pattern of responses, with significantly less correct auditory (73.4%) than visual (81.3%) responses ($z = 2.99$, $p < 0.01$) in the 'easy' task; but significantly more correct auditory (82.4%) than visual (70.7%) responses ($z = 10.17$, $p < 0.01$) for

Table 3.1.

Proportions of correct responses for each task by condition for data partitioned by goodness of fit to the parallel processing model.

	Easy condition		Difficult condition	
	Auditory	Visual	Auditory	Visual
Parallel processing				
Mean	0.944	0.891	0.896	0.819
SD	0.017	0.017	0.014	0.014
z score	2.61	0.56	3.33	2.29
probability	<0.01	>0.05	<0.01	<0.05
sample size	10	10	7	7
Other				
Mean	0.734	0.813	0.824	0.707
SD	0.027	0.027	0.014	0.014
z score	6.25	3.30	1.89	10.39
probability	<0.01	<0.01	>0.05	<0.01
sample size	4	4	7	7

the 'difficult' task. A breakdown of the mean percentages of correct responses by partition is shown in Table 3.1.

At the completion of the study, each subject answered a short questionnaire about their perception of both single and dual-task performance. In the first set of questions, subjects were asked which of the single tasks they found the most difficult and whether they had used any type of strategy as an aid to task discrimination. Of the 14 subjects involved in the study, ten reported that they found the visual task more difficult than the auditory task and indicated that they preferred the auditory to the visual task. They also reported using a variety of simple strategies for both tasks. For instance, a number of subjects reported that they had fixated on one side of the cue to discriminate the visual task. Similarly, a strategy using the different audible patterns of 'high-low' and 'low-high' tones was commonly reported for the auditory task.

The second set of questions, which related to dual-task performance, was primarily intended to assess how many subjects were able to process both tasks simultaneously, and how many used some form of strategy that eliminated the need to process both tasks at the same time. The responses from all 14 subjects indicated that none was able to perform both tasks at the same time. Furthermore, all 14 reported using a similar type of strategy; namely, to process the perceptual component of one task before 'attending' to the second task. In other words, all subjects reported using what is essentially a time-sharing strategy. However, the form of strategy which different subjects used varied. Ten subjects reported attending to the visual task and then recalling the auditory pattern from memory after they had decided on which visual stimulus was presented. The other four indicated that they had initially attended to the auditory task and then switched attention to the visual task only after they had memorized the pattern of auditory tones.

Table 3.2.

Proportions of correct responses for the preferred and non-preferred tasks by condition.

	Easy condition		Difficult condition	
	Preferred	Non-pref.	Preferred	Non-pref.
Mean	0.926	0.826	0.888	0.735
SD	0.008	0.008	0.010	0.010
z score	3.27	9.02	3.90	11.81
probability	<0.01	<0.01	<0.01	<0.01
sample size	14	14	14	14

Thus, it was evident from the responses to the questionnaire given by the 14 subjects that at least two clearly different strategies were used to perform the dual-task discrimination, depending on which task was perceived to be the most difficult and which task subjects preferred to perform first. The results of the questionnaire allowed the auditory and visual responses from each subject to be assigned to one of two categories; either the preferred task (i.e. the task initially attended to), or the non-preferred task (i.e. the task subjects chose to perform last).

According to the null hypothesis (i.e. the parallel processing model), both the preferred and non-preferred tasks should be performed at approximately the same level of accuracy; essentially that determined by the assigned level of single-task performance. Analysis of the percentages of correct responses for the preferred and non-preferred tasks resulted in a significant difference between subjects ($F = 3.76$; *d.f.* = 1,39; $p < 0.01$), tasks ($F = 43.08$; *d.f.* = 1,39; $p < 0.01$) and conditions ($F = 11.28$; *d.f.* = 1,39; $p < 0.01$), with the preferred task being performed significantly better than predicted in both conditions, and the non-preferred task being performed significantly worse than predicted in both conditions. However, the task x condition interaction was not significant ($F = 1.83$; *d.f.* = 1,39; $p > 0.05$). Details of the percentage of correct responses for the preferred and non-preferred tasks are shown in Table 3.2.

Discussion

The lack of homogeneity in the dual-task data indicates that the performance of both tasks in each condition varied considerably. However, it is apparent that this result came about largely because different subjects performed the dual-task in a different manner. Analysis of the data indicated that ten of the 14 subjects in the easy condition and seven of the 14 in the difficult condition performed the dual-task in accordance with the parallel processing model. On the other hand, the data from about half the remaining subjects were consistent with the alternative model - the single-channel hypothesis.

Nevertheless, an underlying pattern is evident with the dual-task data. Subjects whose data were consistent with the parallel processing model typically performed both the visual and auditory tasks very accurately; far more accurately than predicted on the basis of single-task performance. However, they were not able to maintain the same level of performance for both tasks in the difficult condition, with the percentage of correct responses for the visual task being significantly less than the predicted level of 85%. Additionally, the responses to the questionnaire also indicated that subjects whose data were consistent with the parallel processing model tended to use the same sequential strategy, with nine of 10 subjects initially attending to and processing information in the visual mode before recalling the pattern of auditory tones from memory for further processing.

While subjects whose data were not consistent with the parallel processing model showed a similar pattern of results in the difficult condition with significantly more correct auditory than visual responses, the performance of four of the 7 subjects in the visual condition was significantly worse than expected (< 78% correct visual responses, $p < 0.05$). Further, it is apparent from the responses to the questionnaire that these four adopted rather complex strategies that may have made the task more difficult rather than simpler. One male subject, for instance, reported that he attempted to limit the amount of information to be processed by listening to the first tone but switching attention to the visual task before the onset of the second tone. Further, the strategy he reported using for the IT task involved fixating consistently on one side of the target and basing his response on whether the short target line was above or below his fixation point. Generally, from the results obtained for this group of subjects, (outlined in Table 3.1), it is apparent that the type of strategies they adopted were less effective than those adopted by the group whose data were consistent with the parallel processing model.

Analysis of the data from each condition grouped according to whether it was the preferred or non-preferred task highlighted just how much the performance of each task differed. The preferred task, for instance, was performed significantly better than predicted in both conditions. In contrast, the non-preferred task was performed significantly worse than predicted in both conditions. Moreover, the significant difference between the predicted and actual level of accuracy of the preferred task could mainly be attributed to performance of the auditory task, since eleven of the 14 subjects indicated a preference for this task. On the other hand, the significantly worse performance obtained for the non-preferred task is essentially the result of visual performance, and possibly reflects the greater level of difficulty associated with that task. Nevertheless, this result raises serious doubts about the effectiveness of the auditory task used in this study.

While the dual-task data from some subjects were consistent with the parallel processing model and some consistent with the single-channel model, a more sensitive analysis indicated that neither model could adequately account for all of the results. Moreover, it is clear from the responses to the questionnaire, as well as the dual-task data, that subjects adopted some form of memory strategy to avoid the difficulty of simultaneously performing both tasks at the same time. Since audible frequencies must be presented for a finite period before they can be accurately perceived, the auditory mechanism is particularly well adapted to the task of storing an 'echoic image' for some time.

This ability to store audible tones was apparently used by many of the subjects as the basis for a dual-task strategy, essentially to overcome the problems associated with processing two signals at the same time. In response to the questionnaire, approximately 70% of subjects indicated that they were able to concentrate primarily on the visual discrimination before recalling the pattern of auditory tones from memory for further processing. The responses obtained from these subjects, which are generally consistent with the raw score data, reflect the difficulty associated with masking audible tones. Further, the ease with which subjects could recover auditory signals from 'echoic' memory probably had an impact on the nature of the dual-task strategy typically adopted. The effectiveness of this strategy is quite apparent from the results; all 10 subjects who reported using this technique performed the auditory task better than predicted, while still maintaining better than average visual discrimination accuracy. Thus, subjects who attempted the dual-task discrimination were unanimous in their view that the processing of both signals was carried out by 'time sharing'.

The vastly superior level of auditory discrimination consistently achieved by the majority of subjects raises serious doubts about the effectiveness of this task as an element in dual-task performance. However, whether the high level of accuracy was entirely the result of problems with the task itself, such as the effectiveness of the backward masking procedure, or whether it was associated with other factors such as inadequate training or an erroneous estimation procedure, is problematical. The variability between the single and dual-task results for the auditory task may, for example, simply reflect the time it takes to learn to perform the ATD task. Thus, when the initial estimate of ATD was taken, subjects may not have reached the level of asymptotic performance required to obtain stable and reliable estimates of auditory discrimination. Hence, further 'practice' during the experimental block resulted in a significant improvement in performance. In the final analysis, the apparent ease with which some subjects performed the auditory task makes it impossible to determine whether or not a single-channel mechanism operates at the decision level.

Chapter 4

Backward masking and psychophysical issues in sensory discrimination.

4.1 *Introduction*

Analysis of the dual-task data from Experiment 3 showed equivocal results. One group of subjects were able to perform the concurrent tasks with high accuracy, at least as accurately as they performed each task separately. Hence, their performance was essentially consistent with parallel processing. On the other hand, many of the remaining subjects were unable to perform the concurrent tasks as accurately as they performed the separate tasks. Thus, the data collected from these subjects were consistent with a single-channel model. However, the responses obtained from the questionnaire administered after the dual-task study was completed indicated that subjects generally found it necessary to adopt a time-sharing strategy to process both tasks together. Further, the majority of subjects reported that they dealt with information in the visual mode before *recalling the pattern of auditory tones from memory* to complete the dual-task. Nevertheless, it was clear that many were able to achieve relatively high accuracy (compared with single-task performance) in the concurrent auditory task, even though their attention was initially directed to the visual task.

The high level of accuracy for the auditory task led to the conclusion that the nature and ease of the tone discrimination influenced the type of strategy adopted. However, from the data available it was impossible to determine whether the results were due solely to inherent difficulties associated with masking auditory tones or whether other factors, such as insufficient practice or an erroneous initial estimate of single-task performance, were also involved. Nevertheless, from responses to the question about dual-task strategies, it seems that subjects could effectively recover auditory information well after the offset of the target stimulus, even though the timing of the auditory target was supposedly controlled by a backward mask. This result raised serious doubts about the effectiveness of the auditory backward recognition masking procedure.

To assess further how concurrent visual and auditory tasks are processed, an attempt was made to devise a backward masking procedure that would allow better control of the target stimulus. While the requirements of the visual IT task were taken into consideration, the main aim was to develop a procedure that would limit the amount of auditory information that can be processed from memory after the onset of the masking stimulus. To avoid a repetition of the same problem with the auditory task arising in future studies, the test-retest reliability of the revised procedure had to be assessed.

4.2 *Backward masking*

Although much research has been directed to the study of the backward masking phenomenon, the precise nature of the masking process is not well understood. However, this work has established a number of empirical rules for effective masking by metacontrast that can be used when designing masking procedures. Kahneman and Wolman (1970), for example, reported that the target stimulus becomes relatively more immune to fundamental alteration by subsequent stimulation as the exposure duration increases up to 100 ms. Kahneman (1967) had previously suggested that complete suppression by metacontrast does not occur if a target stimulus is presented for more than 100 ms. Furthermore, early research into the backward masking phenomenon indicated that when the target and masking stimuli are similar in contrast and energy, metacontrast suppression for a task involving a judgement of comparative brightness is a U-shaped function of the temporal separation between the two stimuli (Kolers, 1962; Schiller & Smith, 1966). Moreover, several studies which have assessed backward masking and apparent changes in brightness have reported optimum metacontrast suppression for ISI values between 50 and 100 ms (Alpern, 1953; Fehrer & Smith, 1962; Schiller & Smith, 1966). While the task for measuring visual IT, which involves a judgement of comparative length, would not be expected to follow the same U-shaped function as a judgement of comparative brightness, it remains to be seen whether or not changes to the IT procedure will allow the type of control of the target stimulus required for the investigation of dual-task performance.

If the results obtained for judgements of comparative brightness are used as a guide for masking by metacontrast, a more effective method for assessing visual discrimination within a backward masking paradigm would require the presentation of a target stimulus for a fixed period of time, followed by a 'blank' interstimulus interval of variable duration and, finally, the application of a backward masking stimulus. Previous studies of auditory backward recognition masking effects have successfully used this type of procedure. Kallman and Morris (1984), for example, developed an auditory task that involved the presentation of a target tone for 20 ms, followed by a 'silent' interstimulus interval of variable duration before the application of an 880 Hz backward masking tone. The results obtained indicated that there were substantial backward masking effects, particularly for ISIs less than 80 ms.

Another methodological issue, particularly relevant to the measurement of visual IT but also important in the context of the present dual-task study, concerns the way information about the target stimulus accumulates over time. IT theorists have generally assumed that the relationship between response accuracy and stimulus duration conforms to the top half of a sigmoid or cumulative normal ogive that passes through a stimulus duration of zero at the 50% level of performance; that is, the chance level of accuracy for a forced choice IT task involving two alternatives. This assumption received empirical support in a study by Smith (1986) which showed that a normal ogive with chance level performance at a stimulus duration of zero provides a good model for both 2, 4 and 8 alternative IT tasks. Further, information about the target is assumed to accumulate in ". . . a perfectly linear manner over time but . . . that various sources of error produce a departure from the straight line to give the cumulative normal curve" (p. 993, Levy, 1992).

More recently however, a review of IT data has raised serious doubts about the validity of this assumption. Referring to the data of Vickers, Nettelbeck and Willson (1972), Levy (1992) noted that ". . . it is evident to the naked eye that the data for a group of university students strikingly and systematically depart from this position" (p. 988). Levy's reanalysis of Vickers, Nettelbeck and Willson's data together with those of Nettelbeck and Young (1989) indicates a significant departure from a stimulus duration of zero for 50% accuracy, with estimates of chance level performance consistent with stimulus exposures of from 10 to 40 ms.

The issue of whether a minimum duration of stimulus exposure is required to encode the target is particularly relevant to dual-task performance where the use of a time-sharing strategy may be a viable option. If the visual and auditory tasks used to measure dual-task performance could be modified so that subjects require a substantial amount of time to make reliable judgements about each target at levels significantly better than chance, the time-sharing option would become less viable. This would occur because the time constraints imposed on each task would limit the subject's ability to gather sufficient evidence about the first target stimulus before switching attention to the second task. On the other hand, if evidence about the target accumulates, at least initially, in a linear fashion, a time-sharing strategy would appear to be a more viable option.

Two experiments were carried out to evaluate the effectiveness and reliability of a revised procedure which included a 'blank' or 'silent' interstimulus interval of variable duration between the offset of the target stimulus and the onset of the backward mask. In Experiment 4, visual performance over a range of stimulus durations and 'blank' ISIs were compared for two masking conditions; the traditional pi-figure mask and the flash mask developed in Experiment 2. In Experiment 5, auditory performance over two stimulus durations and ISIs were compared under two conditions; one with a background of 'white noise' and the other without 'white noise'.

4.3 *Experiment 4*

Method

Subjects

Twenty four first-year apprentices (22 males and 2 females) indentured to Mitsubishi Motors Australia Ltd. agreed to take part in this study. Their ages ranged from 17 to 19 years (mean = 18, SD = 1). At the outset, subjects were tested for visual acuity using a Snellen Eye Chart. All were found to have normal or corrected-to-normal vision. Before participating in this study, subjects were naive about the aim of the experiment.

Apparatus

Stimuli were displayed using a Gerbrands G-1130 3-field tachistoscope, converted in-house to four fields. One quick-change card holder was replaced with a fixed card holder which allowed the installation of a 3 mm diameter light emitting diode (LED) used as a cue. The timing for each field and the LED was via a modified Series 300 digital timer. Stimulus sequences and durations were preprogrammed and controlled by a North Star Advantage computer. A response was made by pressing one of two buttons on a response panel located at the base of the tachistoscope.

Stimuli

The target stimulus consisted of two vertical lines 25 and 35 mm in length, 10 mm apart and closed at the top by a short horizontal line, drawn on white 100 by 150 mm index cards in 1 mm thick black india ink. The 'left' stimulus had a short vertical line on the left side; the 'right' stimulus was a mirror image of the left. Two masking techniques were used; the first was the commonly used pattern overlay in the form of a pi-figure [see Figure 2.2]; the second was the flash mask [see Figure 2.3]. The viewing distance for all stimulus material was fixed at 80 cm. Luminance level for the four fields was uniform, and set at approximately 6 cd/m^2.

Procedure

Each trial consisted of the presentation of a 3 mm faint red cue (1000 ms), a target stimulus (exposed for either 10, 15, 20 or 25 ms), followed by a 'blank' interstimulus interval of either 20, 40, 60 or 80 ms (consisting of a plain white index card) and finally a backward mask of 350 ms duration. The period between the conclusion of a response to the previous trial and the initiation of the next was 2500 ms. In condition 1, the procedure for session 2 was essentially the same as for session 1, but with the other masking procedure. For condition 2, the order of presentation for mask was reversed. Each subject attended two experimental sessions about one week apart, one for each version of the two masking procedures. The first session lasted about 1 hour and the second about 45 minutes, approximately one third of the time in both sessions being taken up with practice. Order of presentation was balanced across subjects.

At the start of the first session, task requirements were carefully explained with the aid of a duplicate set of stimulus cards. Instructions emphasized accuracy, not speed, and stressed that responding was to the shorter of the two target lines by pressing the appropriate button on the response panel. Initial practice involved a minimum of 120 trials; 10 trials at 25 ms stimulus duration and a 150 ms ISI before the application of the backward masking stimulus; 10 trials at 25 ms stimulus duration and 100 ms ISI; 10 trials at 20 ms stimulus duration and 80 ms ISI; 10 trials at 20 ms stimulus duration and 60 ms ISI; 20 trials at 15 ms stimulus duration and 60 ms ISI; 20 trials at 15 ms stimulus duration and 40 ms ISI; 20 trials at 10 ms stimulus duration and 40 ms ISI and finally 20 trials at 10 ms stimulus duration and 20 ms ISI. Further practice at any of these exposures was given, if necessary, until subjects were familiar with the requirements of the task. Following practice, subjects were given a test session involving a single block of 256 trials, 16 for each of the 16 stimulus duration and ISI combinations, arranged in random order, and with equal numbers of left and right responses for each combination.

The second session was essentially the same as the first, with the same practice arrangements, but, since subjects were already familiar with the basic task (other than the mask configuration), the introductory briefing was less detailed. Prior to the experimental block of trials in session 2, subjects were given a short series of unmasked trials at stimulus exposures of 10, 15 and 20 ms. At the completion of each experimental session, subjects answered a short questionnaire about the way in which they had performed the task and whether they had used any specific strategies to make the task easier. Following the second session, subjects were asked whether they found the condition with the pi-figure mask or the condition with the flash mask the most difficult.

Results

The results of the unmasked trials indicated that subjects had little difficulty discriminating the IT target in the absence of a backward masking stimulus, with twenty two of 24 subjects achieving 100% accuracy at 15 and 20 ms stimulus duration, respectively, (mean = 98%) and twenty one of 24 achieving 100% accuracy at a stimulus duration of 10 ms (mean = 97%).

The data obtained on masked trials for each order of mask presentation and type of mask for stimulus durations of 10, 15 20 and 25 ms are displayed in Figure 4.1, 4.2, 4.3 and 4.4, respectively. The raw scores for each group of subjects for two masking conditions and orders of mask presentation at four stimulus durations were analysed for trends using a factorial design with repeated measures over ISI. A full summary Table for this analysis is included in Appendix 4.5. The results confirmed a significant linear trend for the number of correct responses over ISIs ($F = 26.97$; *d.f.* = 1,22; $p < 0.01$) as expected on the basis of past research. A significant difference was found between linear trends for each stimulus duration ($F = 4.43$; *d.f.*= 3,66; $p < 0.05$). Additionally, there were significant higher order non-linear effects; an overall quadratic component ($F = 7.16$; *d.f.* = 1,22; $p < 0.01$) and an order of presentation x mask x stimulus duration quadratic trend. There was also a significant cubic component ($F = 10.64$; *d.f.* = 1,22; $p < 0.01$) and an order of mask presentation x stimulus duration cubic interaction ($F = 4.82$; *d.f.* = 3,66; $p < 0.01$). The results also indicated that there were significant main effects for order of presentation ($F = 7.27$; *d.f.* = 1,22; $p < 0.05$), mask ($F = 20.62$; *d.f.* = 1,22; $p < 0.01$) and stimulus duration ($F = 35.95$; *d.f.* = 1,22; $p < 0.01$). Furthermore, there were significant

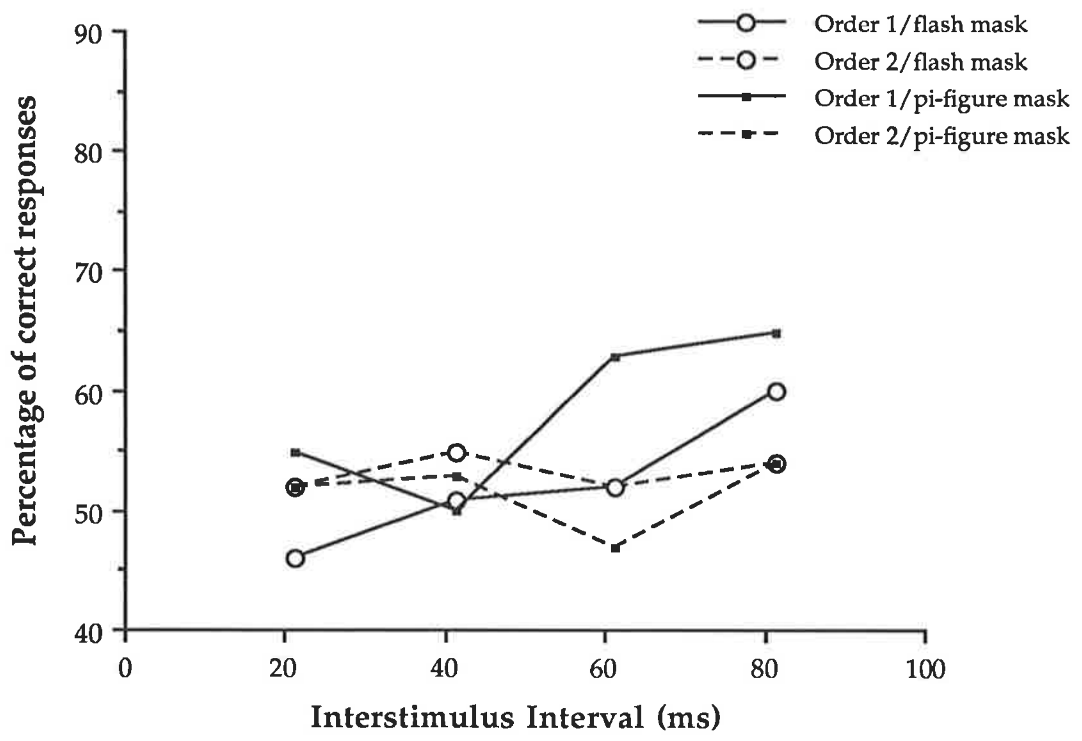


Figure 4.1. Percentage of correct responses as a function of ISI for a stimulus duration of 10 ms. Each subject performed the IT task under two types of backward masking conditions; the traditional pi-figure mask and the flash mask. The order of presentation was balanced across subjects.

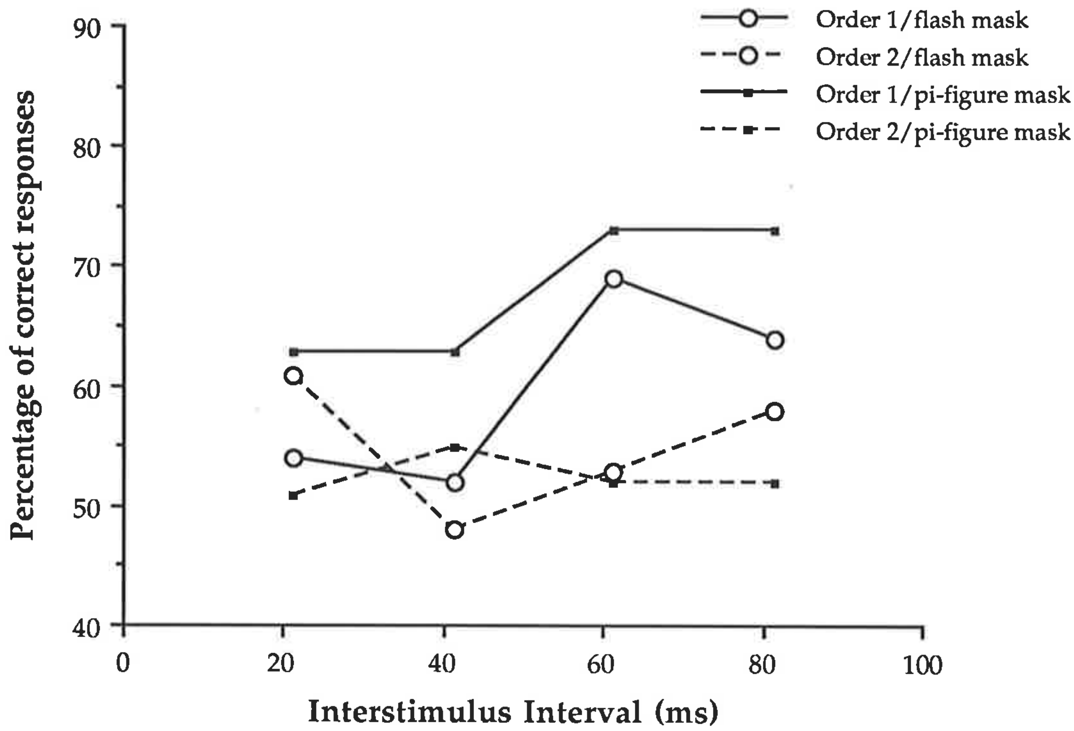


Figure 4.2. Percentage of correct responses as a function of ISI for a stimulus duration of 15 ms. Each subject performed the IT task under two types of backward masking conditions; the traditional pi-figure mask and the flash mask. The order of presentation was balanced across subjects.

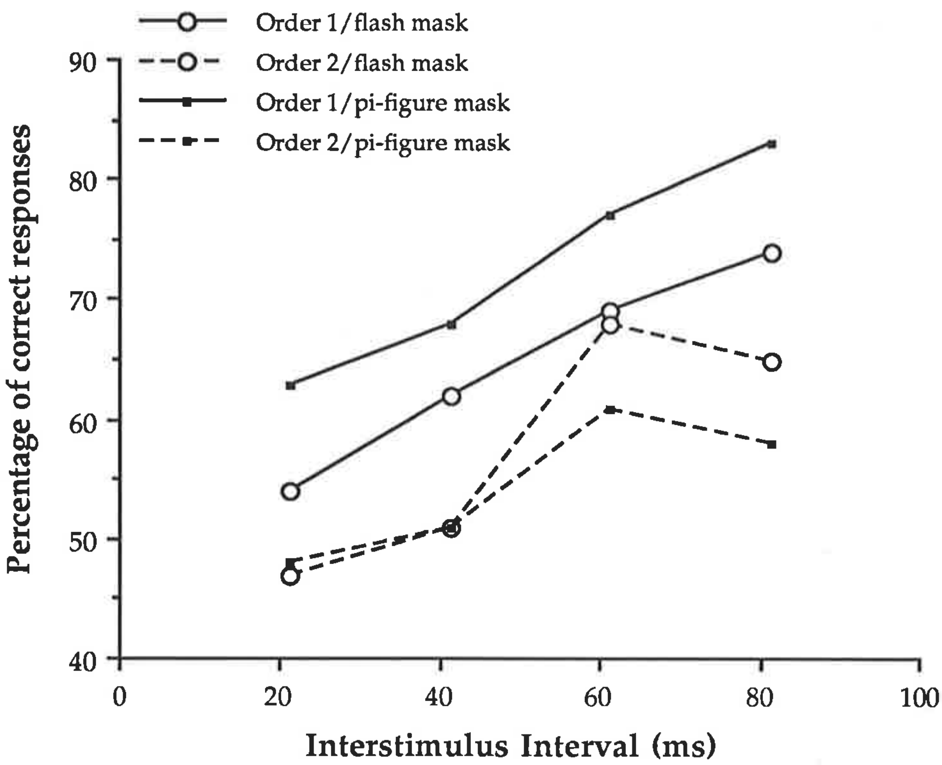


Figure 4.3. Percentage of correct responses as a function of ISI for a stimulus duration of 20 ms. Each subject performed the IT task under two types of backward masking conditions; the traditional pi-figure mask and the flash mask. The order of presentation was balanced across subjects.

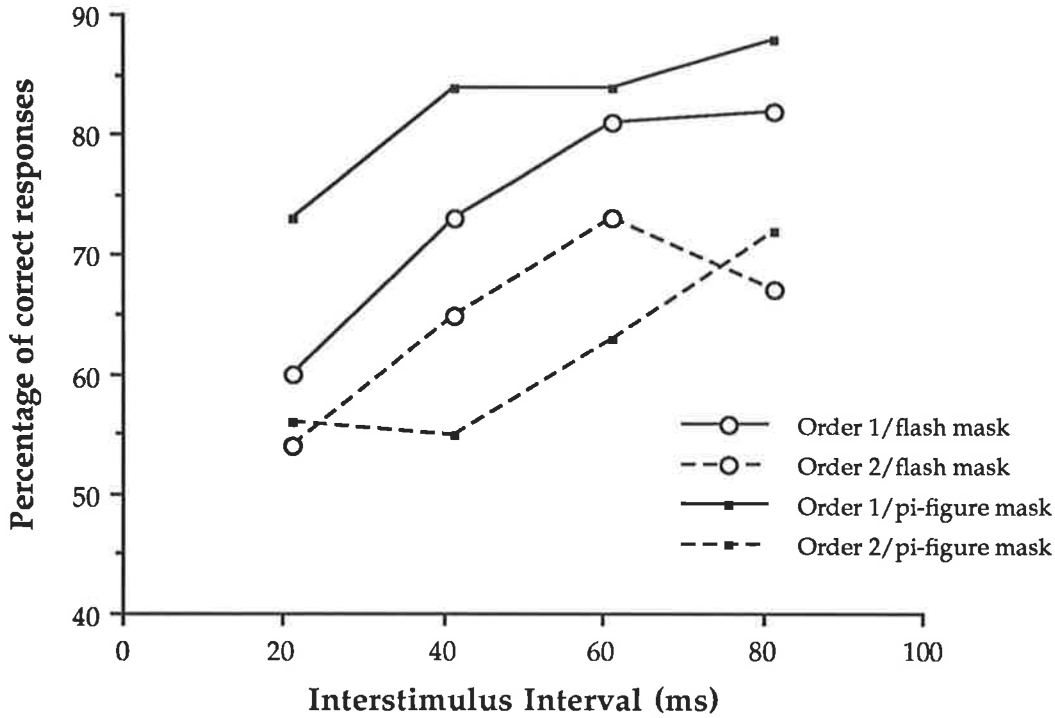


Figure 4.4. Percentage of correct responses as a function of ISI for a stimulus duration of 25 ms. Each subject performed the IT task under two types of backward masking conditions; the traditional pi-figure mask and the flash mask. The order of presentation was balanced across subjects.

order of presentation x mask ($F = 4.90$; *d.f.* = 1,22; $p < 0.05$) and order of presentation x stimulus duration ($F = 4.89$; *d.f.* = 1,22; $p < 0.05$) interactions.

The percentage of correct responses obtained for each stimulus duration and ISI indicate that subjects required an appreciable amount of time to encode the target stimulus. This is particularly evident from the level of accuracy achieved at short stimulus durations and ISIs, which was generally no better than that expected by chance. At a stimulus duration of 10 ms, for example, the performance of the group of subjects who attempted the task involving the flash mask in the first session (Order 1) was only significantly better than the 50% chance level at an ISI of 80 ms, with a mean of 59% correct responses. A similar result was obtained for a stimulus duration of 15 ms, with performance no better than chance at the shortest ISIs of 20 and 40 ms. However, at longer ISIs, performance improved significantly with a mean of 68% at an ISI of 60 ms and 63% at an ISI of 80 ms. When the stimulus duration was increased to 20 ms, the percentage of correct responses were also significantly better than chance level for all but the shortest ISI, with 61% correct at 40 ms ISI, 68% correct at 60 ms ISI and 73% correct at 80 ms ISI. Further, at the longest stimulus duration of 25 ms, performance was consistently better than chance for all ISIs, with 59%, 72%, 80% and 81% correct for ISIs of 20, 40, 60 and 80 ms, respectively.

In contrast to the results obtained in the first session in which the flash mask was used to control the stimulus exposure, subjects were generally able to perform the task set in session 2, involving the pi-figure mask, at a much higher level of accuracy. The mean percentage of correct responses for all but the trials at the shortest stimulus duration of 10 ms and ISIs of 20 and 40 ms were significantly better than chance level, ranging from 62% correct at a stimulus exposure of 15 ms and an ISI of 20 ms, to 87% correct at the longest stimulus duration and ISI of 25 and 80 ms, respectively.

On the other hand, subjects assigned to the condition in which the first session involved the pi-figure mask (Order 2) were only able to perform the IT task significantly better than the 50% chance level at stimulus exposures of 20 and 25 ms and ISIs of 60 and 80 ms. And although the overall performance of this group was better in the session involving the flash mask (session 2), it was not as consistent as the performance of the other group. At a stimulus duration of 15 ms and ISI of 20 ms, for example, the group scored 60% correct; but at the same stimulus exposure and ISIs of 40 and 60 ms, they could only manage about 50% correct responses. At the longest ISI of 80 ms, however, the group averaged better than chance level, with 57% correct responses. The results of trials at longer stimulus exposures were more consistent, with means of 67% and 64% at a stimulus duration of 20 ms and ISIs of 60 ms and 80 ms, and 64%, 72% and 66% at a stimulus exposure of 25 ms and ISIs of 40 ms, 60 ms and 80 ms, respectively. The mean percentage of correct responses by stimulus duration and ISI for each order of presentation and type of backward mask are displayed in Appendix 4.4.

In response to the questionnaire administered after each test session, eleven of 24 subjects reported adopting a strategy based on apparent movement for the pi-figure mask, but only two reported attempting to use the same type of strategy for the flash mask. When questioned about the relative difficulty of the two masking procedures, 9 subjects indicated that they found the condition involving the flash mask the most difficult, 11 indicated that they found the trials with the pi-figure mask the most difficult, and four indicated that they found no difference between the two masks. However, it is evident from responses given that most subjects were biased in reporting the task they had just completed as the most difficult.

Discussion

The effectiveness of the backward masking technique is evident from a comparison of the results obtained on masked versus unmasked trials. In the absence of a backward masking stimulus, the majority of subjects were able to discriminate the IT target with 100% accuracy. In contrast, discrimination of the target overlaid by a backward masking stimulus was clearly much more difficult. For example, at the longest stimulus duration of 25 ms and an ISI of 80 ms, the mean percentage of correct responses ranged from 72% to 81% for the flash mask, and 71% to 87% for the pi-figure mask.

It is evident from the outcome of this study that subjects were unable to consistently perform the IT discrimination task at short stimulus durations and ISIs any better than would be expected by chance. The results suggest that subjects typically require a stimulus exposure of approximately 20 ms to reliably encode the IT target. For example, under both masking conditions, subjects found it difficult to score better than chance level at stimulus durations of 10 and 15 ms and ISIs of 20 and 40 ms. Nevertheless, at a stimulus duration of 15 ms, performance improved significantly as the ISI increased progressively from 40 to 60 to 80 ms. A similar pattern of responses was evident for a stimulus duration of 20 ms; however, at this stimulus exposure, subjects were generally able to achieve significantly more than 50% correct responses at shorter ISIs. Trend analysis indicated that the pattern of responses observed was best described by a quadratic curve. The resulting function was quadratic in nature because the level of accuracy achieved at short stimulus durations was virtually constant at 50% correct for ISIs of 20 and 40 ms, only improving beyond chance level as the ISI increased to its maximum value of 80 ms. This result is consistent with Levy's (1992) proposal that a stimulus duration of the order of 10 to 40 ms is required for subjects to gather sufficient information about the target stimulus to perform the task reliably at better than the 50% chance level.

The results of Experiment 4 also indicate that there was a significant difference between the response accuracy under each masking condition, although this was confounded to some extent by an unexpected order of presentation effect. Nevertheless, the general pattern of results indicate that the flash mask was more effective, with discrimination of the IT target overlaid by the pi-figure mask more accurate than discrimination of the same target stimulus overlaid by the flash mask. Further, the significant mask x stimulus duration x order of presentation quadratic interaction reflects the different pattern of responses resulting from the difficulty subjects had performing the discrimination task under each masking condition and stimulus duration. Although discrimination accuracy was essentially the same at short stimulus durations and ISIs, as the ISI increased, performance for trials involving the pi-figure mask was generally more accurate than on trials involving the flash mask. Moreover, the difference in performance under each masking condition was accentuated as the stimulus duration increased up to its maximum value of 25 ms.

There were also substantial practice effects, apparent from the significant order of presentation x mask interaction. However, the practice effect for each order of presentation was different. Subjects assigned to Order 1, for example, who performed the task involving the 'flash' mask first subsequently performed the second task involving the 'pi-figure' mask much more accurately. On the other hand, subjects assigned to Order 2, who were required to perform the task involving the pi-figure mask first, only performed the second task involving the 'flash' mask marginally better than the first task. This result is consistent with that found in Experiment 2 (see also Evans & Nettelbeck (1993) for the published version), where it was argued that the flash mask effectively limits the subjects ability to use a strategy based on apparent movement.

The presentation technique used for the present study allows much better control of the target stimulus than the method involving presentation of the target for a variable duration. The percentage of correct responses at the longest stimulus duration and ISI, equivalent to a stimulus-onset-asyncrony (SOA) of 105 ms, was considerably less than that found in Experiment 2, with 71% correct responses for trials involving the 'flash' mask and 87% accuracy for trials involving the 'pi-figure' mask. Moreover, this technique, coupled with the 'flash' mask makes accurate discrimination of the IT target a more difficult task than the technique and masking stimulus commonly used thus far to obtain measures of IT.

Summary

Three points are clear from the results of this study. Firstly, the task involving a 'blank' ISI between the offset of the target and the onset of the mask provides better control of the IT target, making the discrimination task more difficult. Secondly, this study confirmed a previous conclusion that the flash mask is more effective in controlling the use of a strategy based on apparent movement than the pi-figure mask. Thus, from a technical point of view, the flash mask offers better control of the target and hence a more accurate estimate of IT than the traditional masking technique. Finally, the results obtained using this procedure indicate that an appreciable stimulus encoding time is required before subjects can reliably perform the discrimination task at better than chance level. Hence, it is clear that if the technique tested in this study is to be used effectively, a stimulus duration of 20 to 25 ms is required for subjects to perform the discrimination task in a reliable manner.

4.4 *Experiment 5*

Experiment 5 was designed to evaluate the reliability of an auditory tone discrimination (ATD) task that involved a 'silent' interval, analogous to the revised method used to obtain an estimate of visual IT in Experiment 4. To assess whether discrimination accuracy was a function of the signal-to-noise ratio, two different ATD conditions were tested. In one condition, the auditory task was imbedded in a background of 'white noise'. The frequency discrimination results for this task were then compared with the a second task involving a measure of ATD without 'white noise'. A third estimate of ATD at a shorter stimulus duration and ISI was compared with the first two estimates to test whether frequency discrimination was influenced by the interval between the onset of the target tone and the onset of the backward masking tone.

It was evident after preliminary testing of the auditory equipment that tones of short duration (for example, 25 ms) were virtually inaudible within the frequency range available from the programmable crystal oscillator. The results of a short pilot study involving three subjects indicated that the minimum target duration necessary for subjects to perform the tone discrimination consistently was of the order of 35 ms.

Method

Subjects

Initially, 12 undergraduate students enrolled in the first-year Psychology course at the University of Adelaide volunteered to take part in this study. However, only ten of the 12 subjects completed the full study, two subjects failing to attend the second experimental session. Ages ranged from 17 to 24 years (mean = 19, SD = 9). At the beginning of the first session, subjects were asked whether they had any hearing defect that would effect performance on an auditory tone discrimination (ATD) task. None of the subjects reported being aware of any hearing problems. At the outset, all subjects were naive about the aims of the experiment.

Apparatus

Pure sine waves ranging from 900 to 1450 Hz were generated by a programmable crystal oscillator controlled through a Series 300 digital timer under the control of a North Star Advantage personal computer. Background 'white noise' was generated by a complex noise chip wired into the tone generator. Tones and 'white noise' were presented to each ear through a set of Pioneer model 8E-6 stereo head phones. During the experimental blocks, frequency changes were adjusted by PEST (Taylor & Creelman, 1967). A response was made by pressing one of two buttons on a panel before the subject.

Stimuli

Target stimuli consisted of pure sine waves in the frequency range 1150 ± 150 Hz. The target duration was set at either 35 or 50 ms, and was followed by an auditory backward recognition masking stimulus consisting of a 1150 Hz pure sine wave of 350 ms duration. The level of intensity of both the target and masking tones was set at 72 dB. One of the experimental conditions involved the same task embedded in a background of 'white noise' with a level of intensity of 68 dB.

Procedure

Subjects attended two experimental sessions, about two weeks apart. The first session lasted about 45 minutes, half of this time being taken up to explain the requirements of the task and with practice trials. The second session lasted about 30 minutes, with approximately one quarter of the time taken up by practice.

Two estimates of ATD, one with and one without 'white noise', were obtained in the first session of this study. The timing of the auditory task was the same for both estimates, consisting of the presentation of a target tone of 50 ms duration, a 'silent' interval also of 50 ms duration, followed by an 1150 Hz backward recognition masking stimulus of 350 ms duration. The initial stimulus deviation was 1150 Hz ± 150 Hz, and thereafter adjusted according to the pattern of correct responses by the computer algorithm PEST. All tones were of constant intensity set at 72 dB. The level of intensity of background 'white noise' was set at 68 dB. Because of limitations within the tone generation equipment, the background 'noise' in the *with* 'white noise' trials was 'on' for the entire duration of the experimental block. Subjects assigned to condition 1 performed the auditory task with 'white noise' first, followed by the auditory task without 'white noise'. The other group of subjects, assigned to condition 2, performed the two ATD tasks in reverse order. A third estimate of ATD, with the duration of both the target tone and ISI set at 35 ms and without a background of 'white noise' was obtained from ten of the 12 subjects in a second session about one week after the first.

Previous experience had shown that subjects found the ATD task difficult unless they could clearly distinguish between the different tones at the introductory stage. Therefore, practice was carefully graded to allow subjects to achieve satisfactory performance at each level before moving to a more difficult level. The introductory practice consisted of 20 trials at a target duration of 100 ms and frequency deviation of 150 Hz; 10 of the 20 trials with an ISI of 250 ms, and 10 with an ISI of 100 ms. Once subjects had achieved 90% accuracy on the second block of 10 trials, they attempted the next level of practice at the same frequency deviation (150 Hz), but a target duration of 50 ms. Practice at this target duration consisted of 10 trials with an ISI of 100 ms, and 10 trials with an ISI of 50 ms. Again, once a level of 90% accuracy was achieved at an ISI of 50 ms, subjects attempted the final practice, consisting of a minimum of 60 trials at a target duration of 50 ms and frequency deviation of 100 Hz, with 20 of the 60 trials at an ISI of 100 ms, 20 with an ISI of 75 ms and 20 with an ISI of 50 ms. Subjects were required to achieved 75% accuracy at an ISI of 50 ms before they attempted the first experimental block of trials.

Practice for the second block of experimental trials, which followed immediately after the completion of the first experimental block, consisted of a minimum of 20 trials, 10 at a target duration of 50 ms, ISI of 75 ms and frequency deviation of 100 Hz, and 10 trials at a target duration of 50 ms, ISI of 50 ms and frequency deviation of 75 Hz. At the completion of practice, subjects immediately started the second experimental block of trials. Practice at the start of the second session for the third estimate of ATD consisted of a minimum of 40 trials, 10 at a target duration of 50 ms, a frequency deviation of 100 Hz and an ISI of 75 ms, and a further 30 trials at a stimulus duration of 35 ms and frequency deviation of 75 Hz, with 10 of the 30 trials at an ISI of 75 ms, 10 at 50 ms and 10 at 35 ms. The experimental trials for the third estimate of ATD followed immediately after the practice session.

Results

Mean frequency discrimination for the two estimates of ATD at a target duration of 50 ms, and the third estimate at a duration of 35 ms are displayed in Table 4.1.

The data gathered in session 1, consisting of the estimates of ATD with and without a background of 'white noise', were initially analysed using a repeated measures analysis of variance. The results indicated that there was no main effect for condition; in other words, frequency discrimination was not affected by the presence of 'white noise' ($F > 0.05$). Moreover, there was no significant difference between the first and second estimates of ATD, nor was there a condition x estimate interaction ($F > 0.05$).

Since the addition of 'white noise' did not have a significant effect on task performance, the first and second estimates obtained in session 1 from 12 subjects, together with the third estimate obtained in session 2 were analysed using a repeated measures Analysis of Variance. The results indicated that there were significant differences between the three measures ($F = 3.84$; $d.f. = 2, 18$; $p < 0.05$). A planned comparison of the means of the three estimates indicated that the significant result was due to the difference in the means of estimates 2 and 3 ($p < 0.05$). Further, the estimate of reliability, calculated from the three estimates across conditions (Appendix 4.6), using Cronbach's α, was 0.79. Details of the raw scores, together with the analysis of variance tables are shown in Appendices 4.6, 4.7 and 4.8.

Discussion

It is evident from the analysis of three estimates of ATD data that the auditory task used in this study provides a reliable index of auditory discrimination, both for estimates taken consecutively, and for those taken some time apart. It is also evident from analysis of estimates 1 and 2 that the

Table 4.1

Mean frequency discrimination (Hz) obtained using the psychophysical algorithm PEST for two tasks; one with and one without 'white noise'. Estimates 1 and 2 were taken in session 1 and estimate 3 in session 2.

	Estimate		
	1	2	3
	with 'white noise'	without 'white noise'	without 'white noise'
Condition 1			
Mean	76	57	84
SD	38	25	16
n	6	6	5
	without 'white noise'	with 'white noise'	without 'white noise'
Condition 2			
Mean	45	33	53
SD	52	8	4
n	6	6	5

The stimulus duration and ISI was set at 50 ms for Estimates 1 and 2 and at 35 ms for Estimate 3.
Note! Estimate 3 was taken without 'white noise' in both conditions.

addition of background 'white noise' did not have a significant effect on the discrimination of auditory tones. However, it should be noted that the level of intensity of the 'white noise' component (68 dB) was much less than the target tone (72 dB). A different result may have been achieved if the intensity of the 'white noise' was closer to that of the target tone. On the other hand, changing the stimulus duration and ISI did have a significant impact on performance. Thus, subjects were not able to discriminate the tones as accurately when the stimulus duration and ISI were set at 35 rather than 50 ms. Therefore, as one would expect, a decrease in both the stimulus duration and the ISI between the offset of the target and the onset of the backward masking stimulus makes accurate tone discrimination more difficult.

The slight improvement in performance from estimate 1 to estimate 2 is consistent with the change expected as a result of practice. However, while subjects were able to discriminate smaller frequency differences more accurately after performing the first block of trials, the difference between the means of the first and second estimates was not significant. Although a significant practice effect would be expected, the large number of actual 'practice' trials which subjects were required to perform may have been sufficient to eliminate the so called 'practice effect' in the experimental blocks. However, the nonsignificant result may have also been influenced to some extent by the small number of subjects who took part in this study, as well as the wide range frequency discrimination results obtained.

Finally, it should be noted that while this study has indicated that the form of ATD task used was reliable, the results obtained in this study do not answer any questions about the effectiveness of the auditory backward masking procedure.

4.5 *Experiment 6*

Two alternative psychophysical methods are commonly used to obtain estimates of IT. One technique, known as the method of constant stimuli (MCS), involves a fixed number of observations at each of several stimulus durations. A study by Nettelbeck, Evans and Kirby (1982), for example, required subjects to respond to 40 observations at each of five stimulus durations. Each set of data collected using the MCS must then be analysed in some way to provide an estimate of IT . Since the function relating response accuracy to stimulus duration is assumed to conform to the top half of a cummulative normal ogive that passes through zero at 50% accuracy, a curve fitting procedure is generally used to fit the data to a psychometric function, from which an estimate of IT may be easily calculated.

However, the majority of recent IT studies have used a different psychophysical technique; either Taylor and Creelman's (1967) parameter estimation by sequential testing (PEST) procedure as previously described; or a staircase method devised by Wetherill and Levitt (1965). Typically, these procedures, which are known broadly as adaptive methods involve a ". . . search for a required IT threshold in which stimulus durations are selected for the next trial according to rules applied to the Ss history of correct and incorrect responding" (p. 992, Levy, 1992).

There have been several important reasons for the shift away from the MCS. One is that the estimation of threshold levels from this type of data is greatly affected by 'chance' errors at long stimulus durations - that is, durations well above the level at which subjects would normally respond with high accuracy. These 'chance' errors are thought to occur from lapses of attention, rather than because of the visibility of the target stimulus. Brebner and Cooper (1986), for example, pointed out that an additional error at a long stimulus duration can increase the estimate of IT at 97.5% accuracy by as much as 15%. Nevertheless, a recent computer simulation study by Levy (1992) indicated that data gathered using the MCS, but analysed using a maximum likelihood rather than a least squares method, provided results that were close to the actual parameters set for the IT simulation.

In contrast to the MCS, adaptive methods essentially limit performance to a small region defining a threshold range. Hence, the outcome of a series of trials is not critically dependent on the mathematical form of the psychometric function (Wetherill & Levitt, 1965). Moreover, since the majority of trials are close to the threshold, the adaptive method is assumed to be more efficient, both in terms of the information content per trial and the number of trials required to reach a pre-defined level of accuracy. Furthermore, adaptive techniques have the added advantage of being relatively simple and easy to use. They also provide an estimate of the threshold level at the completion of trials, without the necessity of further data analysis.

However, while the use of adaptive methods is becoming more frequent, there is some evidence to suggest that the estimates they provide are also of questionable accuracy. Further analysis of the properties of PEST by the original authors, for example, raised some concerns about the accuracy of the procedure. The study, carried out by Taylor, Forbes and Creelman (1983), found that the application of the original parameter estimation rules resulted in signal detection estimates that were consistently different than those obtained by a fixed level procedure.

To test the reliability and consistency of two different procedures, baseline measures of IT and ATD were obtained using an adaptive psychophysical method based on the rules outlined by Wetherill and Levitt (1965). The raw data from each subject were subsequently reanalysed using the SPSS-X Probit package utilizing the maximum likelihood statistic to give a second estimate of the 90% threshold level. The two estimates for each task were subsequently assessed using a repeated measures reliability analysis and paired comparison '*t*' test.

Method

Subjects

Fifteen undergraduate students (5 males, 10 females) enrolled in the first-year Psychology course at the University of Adelaide were recruited to take part in this study. All 15 subjects completed the visual IT task satisfactorily. However, after extensive practice, three subjects (1 male, 2 females) were unable to meet the minimum performance criterion for the auditory task, thus reducing the ATD sample size to 12. Ages ranged from 17 to 39 years (mean = 21, SD = 5). At the beginning of the test session, subjects were tested for visual acuity using a Snellen Eye Chart. All were found to have normal, or corrected to normal vision. They were also asked if they had any specific hearing defects that would effect performance on a tone discrimination task. None of the subjects reported knowledge or history of any hearing problem. At the outset, all subjects were naive about the aim of the experiment.

Apparatus

Two experimental tasks were used in this study; one visual and the other auditory. Visual stimuli were displayed using a Gerbrands G-1130 3-field tachistoscope, converted in house to four fields. Luminance level for the four fields was constant throughout the experimental trials, and set at approximately 6 cd/m^2. The auditory signals were pure sine waves with a frequency band in the range 900 to 1450 Hz produced by a signal generator which incorporated a programmable crystal oscillator. Background 'white noise', used for the auditory trials was produced by a complex noise chip built into the tone generator. Tones were presented through Pioneer Model 8E-6 stereo headphones to both left and right ears. The timing of both visual and auditory stimuli was via a modified Series 300 digital timer, controlled by a Telex Model 1280 personal computer. Stimulus sequences for both tasks were controlled by an adaptive staircase method incorporating an Up-and-Down transformed response rule (Wetherill & Levitt, 1965). Visual responses were recorded by pressing one of two buttons located horizontally on the right side of a response panel. Two button, located vertically on the left hand side of the same panel were used to record auditory responses.

Stimuli

The visual target stimulus consisted of two vertical lines 25 and 35 mm in length, 10 mm apart and closed at the top by a short horizontal line, drawn on white 150 by 100 mm index cards in 1 mm thick black India ink. The 'left' stimulus had a short vertical line on the left side; the 'right' stimulus was a mirror image of the left. The masking stimulus was the flash mask developed and tested in Experiment 2. The viewing distance for all stimulus material was fixed at 80 cm. The auditory task consisted of two tones; a 35 ms target stimulus of variable frequency; and a 1200 Hz backward recognition masking stimulus. The level of intensity for both the target and masking tone was set at 72 dB. All tones were imbedded in a background of 'white noise', as described previously for Experiment 5 but with the intensity level increased from 68 to 70 dB.

Procedure

Each subject completed two separate tasks during an experimental session that lasted approximately 75 minutes. The first task was a measure of visual IT; the second, an auditory tone discrimination task; both tasks being essentially the same as those tested in Experiments 4 and 5. After giving a brief description of the two experimental tasks, the procedure for the visual task was explained in detail. Each visual trial consisted of the presentation of a 3 mm diameter red dot which acted as a cue (1000 ms), a target stimulus (35 ms), a 'blank' interstimulus interval (ISI) of variable duration followed by a backward masking stimulus (350 ms). The minimum period between the conclusion of a response to the previous trial and the initiation of the next was 2500 ms. The stimulus sequence was demonstrated using a duplicate set of cards. It was carefully explained that responding should be to the shorter line, and that accuracy, rather than speed, was the most important performance criterion. The procedure for recording left and right responses was also demonstrated. Before attempting the visual experimental block, subjects were given at least 100 practice trials so that they were familiar with the task. The stimulus duration and ISI for the initial practice, consisting of a block of 10 trials was set at 75 and 150 ms, respectively. This was followed by a block of 30 trials, with a stimulus duration of 50 ms, 10 of the 30 at an ISI of 150 ms, 10 at an ISI of 125 ms and 10 at an ISI of 100 ms. The final practice consisted of a minimum of 50 trials with a stimulus duration of 35 ms; 20 at an ISI of 100 ms, 20 at an ISI of 75 ms and finally, 10 at an ISI of 50 ms. Further practice at any of these exposures was given if required. Subjects were required to achieve at least 90% accuracy at a stimulus duration of 35 ms and ISI of 75 ms before continuing with the last practice and experimental blocks. Immediately following the practice trials, an estimate of IT at a stimulus duration of 35 ms was obtained using an adaptive staircase method outlined by Wetherill & Levitt (1965). The target exposure was set at 35 ms throughout the experimental trials. Initially, the ISI was set at 75 ms. It was subsequently shortened for a series of correct responses, but lengthened for a series of incorrect responses. On average, 82 trials were required to achieve an estimate of IT at the 90% level.

At the completion of the visual task, subjects were briefed about the auditory task, which was described as an auditory equivalent of visual IT. For the auditory task, each trial consisted of a variable frequency target tone with an exposure duration of 35 ms, a 'silent' ISI of the same duration as the subject's ISI previously established for visual IT, followed by a 1200 Hz backward recognition masking tone that lasted 350 ms. The frequency of 'high' and 'low' tones varied equally about the 1200 Hz masking tone. As has been described in detail for Experiment 5, there was a background of 'white noise' present for the duration of the auditory trials. The minimum time between successive trials was 2500 ms. The auditory task was demonstrated using long bursts of tones; either a 1400 Hz target tone followed by the 1200 Hz mask in the case of a 'high' response, or a 1000 Hz target tone followed by the 1200 Hz mask for the 'low' response. The procedure for recording both 'high' and 'low' responses was demonstrated, and again, it was stressed that performance accuracy rather than speed was the main criterion. Initial practice consisted of 60 trials at a stimulus duration of 75 ms and frequency deviation of 150 Hz, with 10 trials each at ISIs of 200, 175, 150, 125 and 75 ms, respectively. Subjects were required to achieve a minimum of 90% correct responses at a stimulus duration and ISI of 75 ms, and a frequency deviation of 150 Hz, before continuing with practice at a more difficult level. Once subjects achieved the performance criterion, they were given further practice at a stimulus duration of 50 ms and ISI of 75 ms, with 10 trials at a frequency deviation of 150 Hz, 10 at 125 Hz and 10 at 100 Hz. Again, subjects were required to achieve 90% accuracy at a frequency deviation of 100 Hz before continuing with further practice. The final practice blocks consisted of 20 trials at a stimulus duration of 35 ms and frequency deviation of 75 Hz, with 10 trials at an ISI of 75 ms and 10 at an ISI of 50 ms; and 10 trials with a stimulus duration of 35 ms, an ISI of 50 ms and a frequency deviation of 50 Hz. Following practice, an estimate of auditory tone discrimination (ATD) was obtained using the same version of the adaptive staircase algorithm as for the visual task. On average, about 100 trials were required to obtain an estimate of ATD.

Results

Means and SDs for estimates of IT and ATD at the 90% level of accuracy obtained using the adaptive staircase algorithm, together with the results of SPSS-X Probit Analysis are set out in Table 4.2. Analysis of the two sets of estimates for each task indicated that both procedures were highly reliable with (Cronbach's) α of 0.91 (*d.f.* = 14; $p < 0.05$) for the two measures of IT and $\alpha = 0.97$ (*d.f.* = 11; $p < 0.05$) for the two measures of ATD.

However, Probit Analysis of the raw data collected for both IT and ATD resulted in larger estimates at the 90% threshold level than those initially obtained from the adaptive staircase method. The mean ISI for IT estimates calculated using the staircase method was 65.3 ms. On the other hand, the mean ISI calculated from the same data using Probit Analysis was 74.0 ms. A paired comparison 't' test indicated that the difference between the two means was significant ('t' = 2.37; *d.f.* = 14; $p < 0.05$). Similarly, the mean frequency discrimination calculated from the data obtained by the staircase method was 76.8 Hz compared with 91.6 Hz for the same data analysed using Probit Analysis. Again, a paired comparison 't' test indicated that the difference between the two means was significant ('t' = 3.52; *d.f.* = 11; $p < 0.01$).

Table 4.2.

Mean and SDs for estimates of IT(ms) and ATD (Hz) for two different psychophysical methods.

	task			
	IT		ATD	
	Adaptive	Probit	Adaptive	Probit
Mean	65.3	74.0	76.8	91.6
SD	20.8	28.2	36.6	47.5
n	15	15	12	12

Discussion

The magnitude of the coefficient of reliability for each task (Cronbach's α) indicates that both procedures provide reliable measures of individual differences in perceptual performance, in the sense that the rankings were essentially maintained regardless of the procedure used. However, the relative size of the estimates obtained using the adaptive staircase method were significantly smaller than those obtained from the same data reanalysed by SPSS-X Probit Analysis. Furthermore, this result was consistent for both visual and auditory task.

This result raises a serious problem for studies which assume that accurate measures of absolute perceptual discrimination can be obtained by psychophysical methods. For example, when estimates of sensory discrimination are subsequently used as baseline measures for further experimentation, errors that exist with the initial data will have undefinable effects on the outcome of these experiments. The implication for dual-task studies, in which baseline performance at pre-determined threshold levels measured using psychophysical methods are compared with the level of accuracy on concurrent tasks, is that the final outcome is only as accurate as the initial baseline estimate. Further, if the initial baseline estimates are potentially subject to error, the results obtained from subsequent dual-task studies must also be questionable.

It is apparent from the results of this study that there are considerable difficulties in obtaining accurate and consistent measures of sensory discrimination. The reality of psychophysical techniques is perhaps best summed up by Levy (1992) who asserted that ". . . it remains a major misconception to regard psychophysics as a body of methods which produce scales whose structural features and substantive interpretations are independent of the procedures employed" (p. 993). Further, he concluded ". . . it would be attractive if it could be assumed that 100 years or so of psychophysics had resolved issues of best or true sensory measurement; but these issues are not resolved and may never be resolved" (p. 1000).

Chapter 5

The effects of task complexity on the discrimination of concurrent tasks

5.1 *Introduction*

Experiments 4, 5 and 6 addressed a number of issues associated with the performance of IT and ATD tasks. The results of these studies have suggested that it may not be possible to estimate precisely the time required to perform sensory discrimination tasks of this nature at a given level of accuracy. The difficulties arise, in part, because human performance is affected by a number of factors; some within the individual, such as fatigue, arousal and motivation; and some external, such as extraneous noise or movement in the surrounding environment. As a consequence, the subject's ability to 'pay attention' to the main task of making judgements about the target stimulus varies considerably over time, not only from one session to the next, but also from one trial to the next. This is particularly apparent when the task involves the presentation of a large number of trials in a short period of time.

There is evidence to suggest that estimates of the time required to make sensory discrimination (like IT and ATD) obtained by the method of constant stimuli (MCS) are significantly effected by momentary changes in concentration (Brebner & Cooper, 1986). It is also likely that changes in the level of concentration will have a similar effect on estimates obtained using adaptive methods. Consider, for example, the adaptive staircase psychophysical procedure proposed by Wetherill and Levitt (1965). The crux of this method is an Up-and-Down Transformed Response (UDTR) rule used to calculate the target exposure for the next trial, based on the subject's performance on past trials. The UDTR rule for estimates of visual IT at the 80% level, for instance, decreases the exposure of the target stimulus by a predetermined amount (for example, *x ms*) following three correct responses in succession, or alternatively, increases the target exposure (by *x/2 ms*) following one incorrect response. Thus, fluctuations in attention that result by chance in a correct response have little effect on the estimate of time required to discriminate a target, since three correct responses are required to change the target exposure to a lower value. On the other hand, lack of attention that results in an incorrect response will lead to an immediate increase in the duration of the target stimulus. Moreover, if concentration wanes over even a short period of time, for example, 10 - 20 sec, 5 - 7 trials may be effected, resulting in a substantial increase in the exposure of the target stimulus. And as vigilance tends to decline towards the end of an experimental session - that is, near the time the adaptive algorithm is about to finish - an increase in target exposure at this time can significantly increase the final value of the estimate being measured.

Therefore, it is apparent that there are a number of issues that make it difficult to obtain precise estimates of sensory discrimination. Moreover, these difficulties are complicated by several factors. It is obviously questionable, for example, given the ubiquity of practice effects in most laboratory tasks, whether the data initially gathered during the course of an experiment actually reflect the 'true' level at which subjects are capable of performing. Furthermore, the IT results in Experiment 6 suggest that there is a degree of uncertainty about the accuracy of the psychophysical procedures typically used to transform the data into a point estimate.

Additionally, a recent study by Deary, Caryl and Gibson (1993) has highlighted other difficulties with measures of visual IT. They found that response probability at a specific stimulus duration was not stationary, but varied in a constrained manner over a period of time. In other words, the subject's ability to perform a task varies at any stimulus duration over time. Deary *et al*. also noted that their result ". . . poses a fundamental problem for those attempting to measure psychophysical responses accurately" (p. 1255). Moreover, they argued that models of psychophysical response which fail to account for these temporal dynamics can never adequately explain performance on this type of task.

As previously indicated in Chapter 4, above, a significant problem arises when using estimates of sensory discrimination, established during one series of experimental trials, for a subsequent experimental task. This problem is related to the nature of the errors associated with the initial estimate. If the errors were of a random nature, then a sufficiently large number of replications would tend to overcome the difficulties, since errors above and below the actual threshold value would tend to cancel one another out. However, the effect of systematic errors like those observed in Experiment 6 will not cancel; instead they will be carried through to later stages of an experiment. More importantly, small but consistent errors in the initial estimates will almost certainly lead to a deviation between the predictions of an independent decisions model and the observed data, since it is assumed that the initial estimates of performance accurately reflect the perceptual ability of those involved.

An alternative method of assessing information processing models, which avoids the difficulties of absolute measurement was outlined by Kantowitz (1985) in his review of the concept of capacity. Kantowitz and Knight (1978) argued that the amount of resources (i.e. capacity) required to perform a task, increased monotonically with the difficulty or complexity of the task. Therefore, more resources are required to perform a 'difficult' task at a given level of accuracy than are required for an 'easy' task at the same level. Thus, as

Kantowitz (1985) indicated, it is possible to differentiate between a number of information processing models by manipulating the complexity of the tasks that must be performed.

As previously indicated in Chapter 1, limited capacity theory assumes that the central mechanism is capable of processing two concurrent stimuli, provided there is sufficient capacity available to process both. Hence, the key prediction of a limited capacity model such as the one proposed by Broadbent (1971) was an interaction between task difficulty and single-task versus dual-task performance, since more difficult tasks require more processing 'capacity'. Therefore, the limited capacity model can be tested by assessing changes in the performance of 'easy' versus 'difficult' variants of the primary task when presented with and without a secondary task (Kantowitz & Knight, 1978). However, a more complete test of this model requires an experiment which uses at least two levels of complexity for each task, to ensure that additivity effects were not the cause of the interaction between the two tasks (Kantowitz, 1985).

On the other hand, according to Welford's single-channel hypothesis, the central processing mechanism can only deal with one signal at a time; if two signals are presented simultaneously, one is assumed to be 'held in store' until the central mechanism has finished processing the first signal. Thus, *any* concurrent signals are assumed to cause interference, since each signal, regardless of the level of difficulty, must wait in turn for access to the central processing mechanism. However, the level of complexity of the signal being dealt with by the central mechanism will have an indirect effect on the processing of the second signal. This occurs because signals can only be 'held in store' for a limited time before the trace begins to fade. Thus, as the time 'in store' increases, the amount of information recoverable from that trace decreases substantially. Nevertheless, the basic prediction of the single-channel hypothesis is that the performance of one of the concurrent tasks will diminish, regardless of the level of complexity of the tasks used.

In contrast to the central processing mechanism of limited capacity and single-channel models, multiple capacity models are based on the assumption that the human information processing mechanism consists of a number of 'structures', each with it's own 'processing capacity'. And while it is assumed that 'capacity' is 'dedicated' to a structure, it is not entirely clear whether it can only be used by that particular structure, or whether there is some sharing of 'capacity' between structures. However, the basic assumptions of multiple capacity models, with regard to manipulation of task complexity, are not effected by this issue. Assume that two tasks are processed in different 'structures' and that there is sufficient 'capacity' available from each structure to perform the complex task singularly at a given level of accuracy. Then the structure must also be able to perform the same task at the same level while the other structure performs the second task, since at least the same amount of 'capacity' is available from each structure for the concurrent tasks. Hence, a multiple capacity model predicts no decrement in the performance of concurrent over single tasks, regardless of the complexity of the tasks involved. Thus, an interaction between task difficulty and single-task versus dual-task performance implies that a strict multiple capacity model is not correct.

To test this distinction, single-task measures of IT and ATD, each with two levels of difficulty, were compared with the performance of the same visual and auditory tasks presented concurrently. The data were analysed using a repeated measures analysis of variance and the results interpreted in terms of the predictions of the information processing models previously described.

5.2 *Experiment 7*

Method

Subjects

Twenty undergraduate students (9 males, 11 females) enrolled in the first-year Psychology course at the University of Adelaide were recruited to take part in this study. All subjects previously reported having normal hearing. Of the initial 20 subjects, seven (2 males, 5 females) did not attend the second session and one (male) failed to meet the minimum performance criterion for the auditory task, leaving a final sample size of 12. The ages of the participants ranged from 16 to 46 years (mean = 23, SD = 9). At the beginning of the first test session, subjects were tested for visual acuity using a Snellen Eye Chart. All were found to have normal, or corrected to normal vision. They were also asked if they had any specific hearing defects that would effect performance on a tone discrimination task. None of the subjects reported knowledge or history of any hearing problem. At the outset, all subjects were naive about the aim of the experiment.

Apparatus

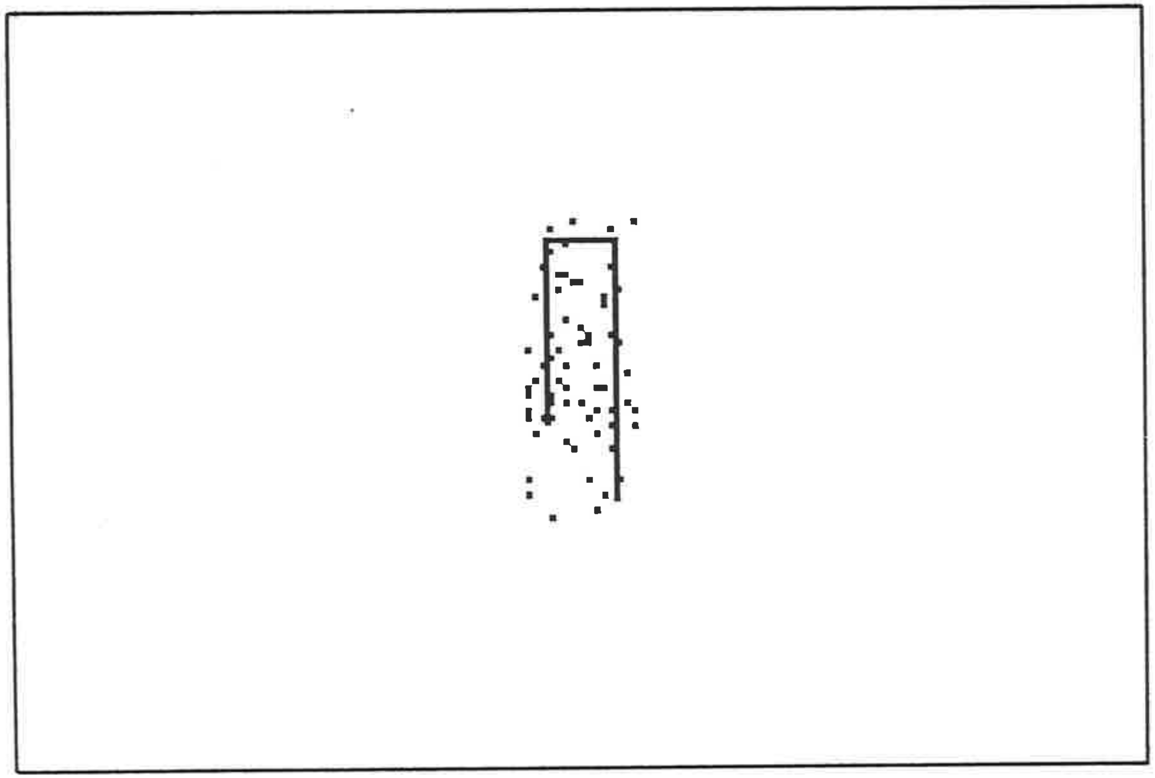
The apparatus used for this experiment was the same as that used for the previous visual and auditory experiments. Both visual and auditory single-task stimulus sequences were controlled by the same version of Wetherill and Levitt's (1965) adaptive staircase procedure as used in Experiment 6. Dual-task sequences were pre-programmed and controlled via a modified Series 300 digital timer by a Telex Model 1280 personal computer .

Stimuli

Two visual and two auditory target stimuli were used in this study; one defined as 'easy' and the other defined as 'difficult'. The 'easy' visual target stimulus consisted of the same two line task used in previous studies overlaid

Figure 5.1

The target stimulus used for the 'difficult' IT target stimulus. The random pattern of dots was generated using a table of ten thousand randomly assorted digits.
The average pattern density is 10%.



with the flash masking stimulus (see Figure 2.3). The 'difficult' visual target consisted of the same two line task imbedded in a visual pattern consisting of a 10% density grid of dots arranged in random order as shown in Figure 5.1. The 'easy' auditory task was essentially the same as the ATD task used in Experiment 6, with the level of intensity of both target and masking stimuli set at 80 dB. The 'difficult' version of the auditory task consisted of 74 dB target and masking tones imbedded in a background of 78 dB white noise.

Procedure

Each subject completed three separate tasks over two sessions about one week apart. The first session lasted about one hour and the second about 45 minutes. In session one, the first task attempted was a measure of 'easy' visual IT. The second was the 'easy' ATD task developed to provide an estimate of threshold discrimination within a time-frame equivalent to visual IT. In the second session, subjects completed four blocks of trials for the single-task condition; one for each of the 'easy' and 'difficult' IT and ATD tasks. This was followed by four blocks of trials for the dual-task condition.

At the start of the first session, subjects were given a brief description of the type of experimental tasks which they were required to perform. They were told that, for each task, there were two levels of complexity, one 'easy' and one 'difficult'. Immediately following the introduction, the 'easy' IT task was explained in detail. Each trial consisted of the presentation of a small red dot which acted as a cue (1000 ms), a target stimulus (35 ms), a 'blank' interval of variable duration, followed by the application of a backward mask (350 ms) designed to stop further processing of the target stimulus. The period between the conclusion of a response to the previous trial and the initiation of the next was 2500 ms. The sequence of events for each trial was demonstrated using a duplicate set of cards. It was carefully explained that responding should be to the shorter line, and that accuracy, rather than speed, was the important performance criterion. The procedure for recording left and right responses was also demonstrated. Before attempting the visual experimental block, subjects were given sufficient practice so that they were familiar with the task. Practice consisted of a minimum of 110 trials, the first 50 at an ISI of 100 ms, with 10 at a stimulus duration of 75 ms, and two blocks of 20 trials with stimulus durations of 50 ms and 35 ms, respectively. This was followed by 60 trials at a stimulus duration of 35 ms, consisting of blocks of 20 trials at ISIs of 75 ms, 50 ms and 35 ms, respectively. Further practice at any of these exposures was given if necessary. All subjects were required to achieve 85% accuracy at a stimulus duration of 35 ms and ISI of 75 ms before continuing practice at shorter exposures. Immediately following the last 20 practice trials, an estimate of IT was obtained using the adaptive staircase algorithm (Wetherill & Levitt, 1965). The target exposure was constant, set at 35 ms. The initial ISI was 75 ms, but shortened for a series of three correct responses, or lengthened after an incorrect response. On average, 45 trials were required to achieve an estimate of IT at the 80% level of accuracy.

At the completion of the visual task, subjects were briefed about the ATD, which was described as an auditory equivalent of visual IT. For the ATD, each trial consisted of the variable frequency target tone of 35 ms duration, a 'silent' ISI (the duration of which was identical to the subject's previously estimated visual IT 'blank' ISI), followed by a 1200 Hz backward recognition masking tone that lasted 350 ms. The frequency of 'high' and 'low' tones varied equally about the 1200 Hz masking tone. The minimum time between successive trials was 2500 ms. The auditory task was demonstrated using long bursts of tones; first, 1400 Hz followed by the 1200 Hz mask to demonstrate a 'high' frequency discrimination, and second, a 1000 Hz tone followed by the 1200 Hz mask for the 'low' frequency discrimination. The procedure for recording both 'high' and 'low' responses was shown to the subject at the same time, and again, it was stressed that accuracy rather than speed was the performance criterion.

Subjects were given considerable practice before attempting the experimental ATD task. There was a minimum of 160 trials; 20 at a frequency deviation of 150 Hz (i.e. 1200 ± 150) and ISI of 150 ms, with 10 trials at a stimulus duration of 100 ms and 10 trials with a stimulus duration of 75 ms. This was followed by 20 trials at 125 Hz variation, 10 with a stimulus duration of 50 ms and ISI of 150 ms, and 10 with a stimulus duration of 35 ms and ISI of 125 ms; and 20 trials at a stimulus duration of 35 ms with 10 at an ISI of 100 ms and frequency variation of 100 Hz and 10 with an ISI of 75 ms and frequency variation of 75 Hz. The final 100 practice trials were given at a stimulus duration of 35 ms with the ISI set at the level previously established for visual IT arranged in 5 blocks of 20 trials with frequencies varying from 125 down to 65 Hz in steps of 20 Hz. Subjects were required to achieve 80% accuracy at stimulus duration of 35 ms, ISI of 100 ms with 105 Hz frequency variation before continuing with the final practice blocks. Following practice, an estimate of ATD was obtained using the same version of the adaptive staircase algorithm as for the visual task. This required approximately the same number of trials as the visual measure of IT.

At the start of the second session, subjects were reminded of the requirements of the two tasks before the 'difficult' variant of each task was briefly described. Two blocks of 20 practice trials were given; one for each of the 'difficult' conditions, starting with the visual task. This was followed by four blocks of 24 single-task trials, one for each mode of presentation and level of difficulty. The task parameters for both the single and dual-tasks were set at the 80% level of accuracy for the 'easy' task calculated by SPSS-X Probit Analysis using the data collected by the adaptive staircase algorithm. The procedure for both the 'easy' and 'difficult' conditions was essentially the same. The 'difficult' visual task involved the presentation of the same cue and backward mask, but a different target stimulus than that used for the 'easy' visual IT task, while the 'difficult' ATD task consisted of the same tone and masking stimulus, but at a lower intensity (74 dB) imbedded in a background of white noise at an intensity of 78 dB.

Immediately after the four blocks of single-task trials were completed, instructions for the dual-task condition were explained. The dual-task consisted of the concurrent presentation of a visual and auditory task. The two levels of each task were combined such that subjects performed both levels of the visual task with both levels of the auditory task in a balanced design. In other words, subjects performed the 'easy' IT task concurrently with the 'easy' ATD task, the 'difficult' IT task with the 'easy' ATD task, and so on.

Subjects were told that the two stimuli, one visual and one auditory, identical to those used in the tasks they had previously completed, would occur simultaneously. They were also told that both tasks were equally important, and that they should try to respond to both as accurately as possible. The dual-task was arranged in four block of 24 trials each, balanced over subjects for the order of presentation of 'easy' and 'difficult' tasks. Between each block of trials, subjects were given a one minute rest. The responses for each trial were recorded by computer and, after the last trial of each block had been completed, compiled in a 2 x 2 matrix. At the completion of the fourth block, subjects were given a short questionnaire about the way in which they had performed both the single and dual-tasks.

Results

The mean percentage of correct responses for the single-task condition are given in Table 5.1. The mean percentage of correct responses for the visual task concurrent with the auditory task, and the auditory task concurrent with the visual task under both 'easy' and 'difficult' conditions are given in Table 5.2 and Table 5.3, respectively. The performance of 'easy' and 'difficult' visual and auditory tasks under both single and dual-task conditions are displayed in Figures 5.2 and 5.3, respectively. A comparison of dual-task performance for 'easy' and 'difficult' visual performance is displayed in Figure 5.4. The same comparison for auditory performance is displayed in Figure 5.5.

Single and dual-task data were analysed by a repeated measures analysis of variance. The results indicated that the order of presentation of the combination of 'easy' and 'difficult' tasks did not have an effect on performance ($F > 0.05$). There were significant main effects for modality ($F = 7.43$; *d.f.* = 1,11; $p < 0.05$) and level of difficulty ($F = 28.35$; *d.f.* = 1,11; $p < 0.01$). However, neither the main effect for task, nor any of the interactions were significant ($F > 0.05$). A planned comparison indicated there was a significant difference between the performance of the visual and auditory tasks in the dual-task condition ($F = 7.61$; *d.f.*=1,8; $p < 0.05$). However, again there was no significant interactions present for either task ($F > 0.05$). A table of results for the Analysis of Variance are displayed in Appendix 5.7

When questioned about the tasks, 10 subjects reported finding the visual task with the pattern stimulus the most difficult; the remaining two indicated that they found the auditory task imbedded in a background of white noise the most difficult. Moreover, none of the subjects reported adopting an apparent movement strategy for either of the visual tasks, although five subject

Table 5.1.

Mean percentage of correct responses for visual (V) and auditory (A) single tasks.

	single-task estimates			
	V(easy)	V(diff)	A(easy)	A(diff)
Mean	98.96	82.64	84.03	81.60
SD	0.18	1.70	1.45	1.22
n	12	12	12	12

Table 5.2.

Mean percentage of correct responses for visual (V) dual-task when performed concurrently with the auditory task.

	concurrent task			
	A(easy)		A(diff)	
	V(easy)	V(diff)	V(easy)	V(diff)
Mean	98.61	89.58	97.92	83.68
SD	0.26	1.39	0.82	1.96
n	12	12	12	12

Table 5.3.

Mean percentage of correct responses for the auditory (A) dual-task when performed concurrently with the visual task.

	concurrent task			
	V(easy)		V(diff)	
	A(easy)	A(diff)	A(easy)	A(diff)
Mean	91.67	84.38	84.72	79.51
SD	0.74	1.19	1.66	1.47
n	12	12	12	12

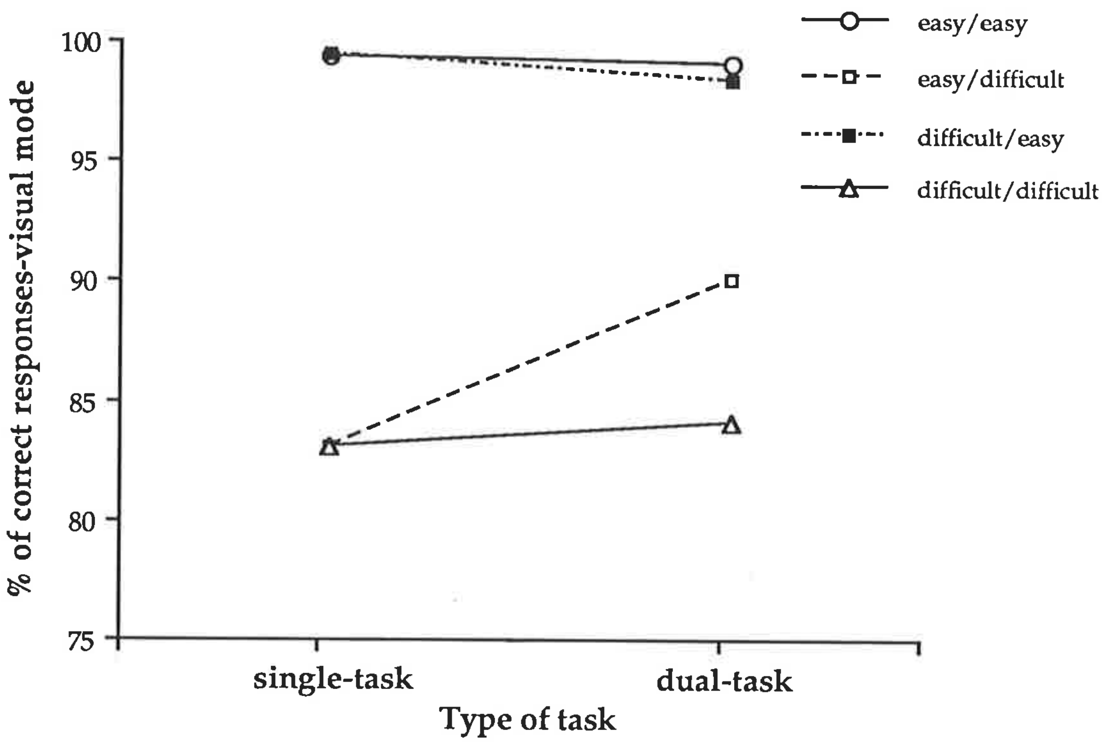


Figure 5.2. Performance of the 'easy' and 'difficult' visual tasks in the single and dual-task conditions. The 'easy/easy' task denotes the 'easy' auditory task performed concurrently with the 'easy' visual task. The 'easy/difficult' task denotes the 'easy' auditory task performed concurrently with the 'difficult' visual task. Similarly the 'difficult/easy' task denotes the 'difficult' auditory task performed concurrently with the 'easy' visual task.

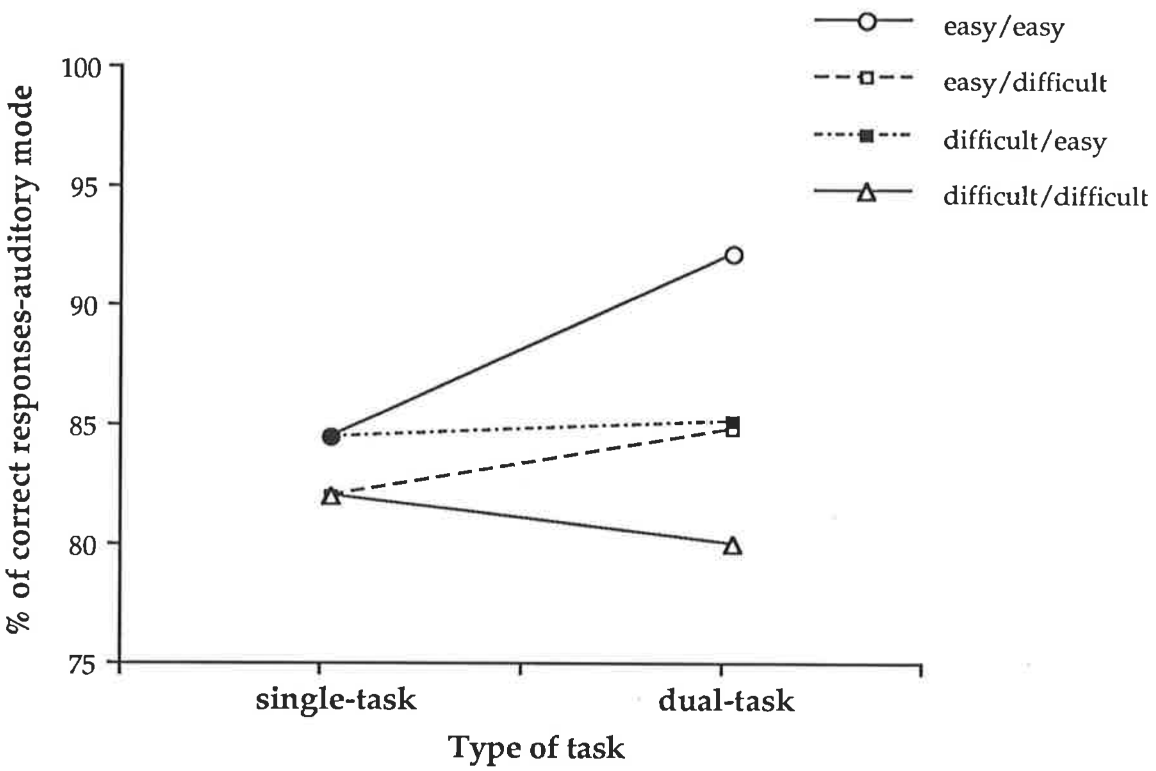


Figure 5.3. Performance of the 'easy' and 'difficult' auditory tasks in single and dual task conditions. The 'easy/easy' task denotes the 'easy' visual task performed concurrently with the 'easy' auditory task. The 'easy/difficult' task denotes the 'easy' visual task performed concurrently with the 'difficult' auditory task. The 'difficult/easy' task denotes the 'difficult' visual task performed concurrently with the 'difficult' visual task with the 'easy' auditory task.

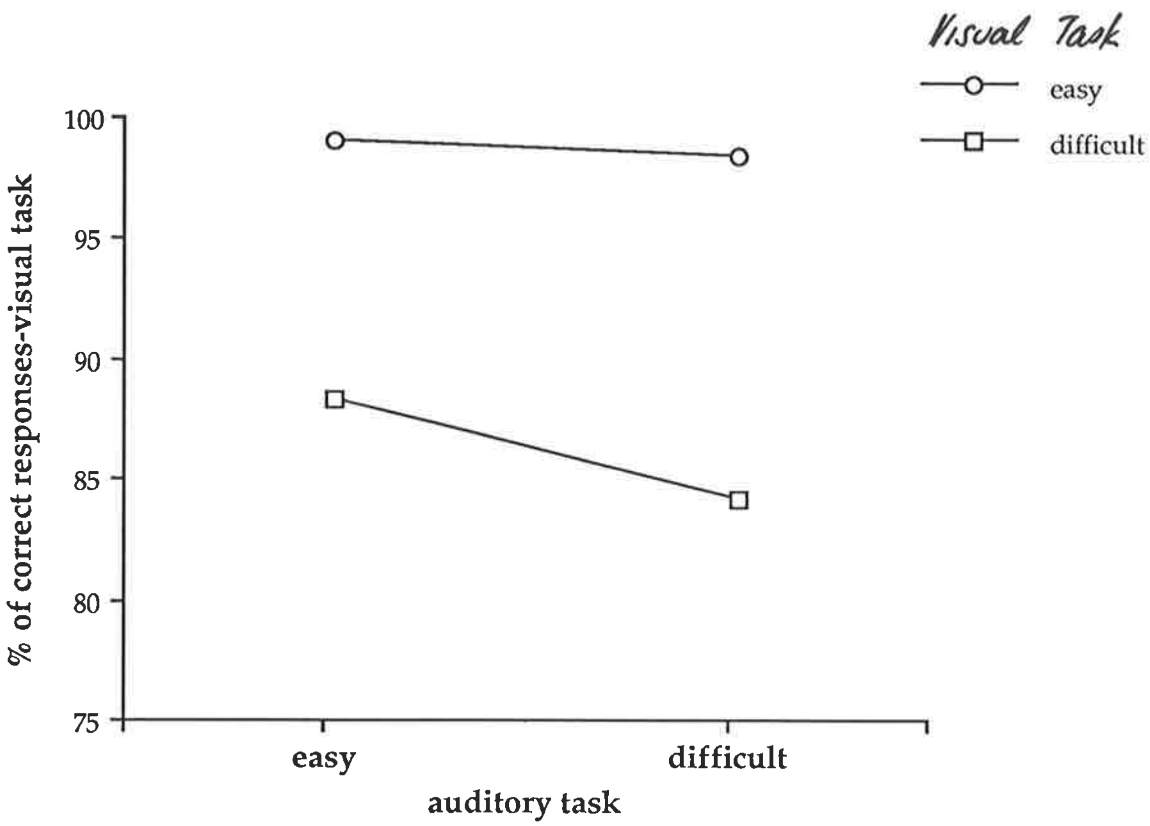


Figure 5.4. Mean percentage of correct responses for the 'easy' and 'difficult' visual task performed concurrently with the 'easy' and 'difficult' auditory task.

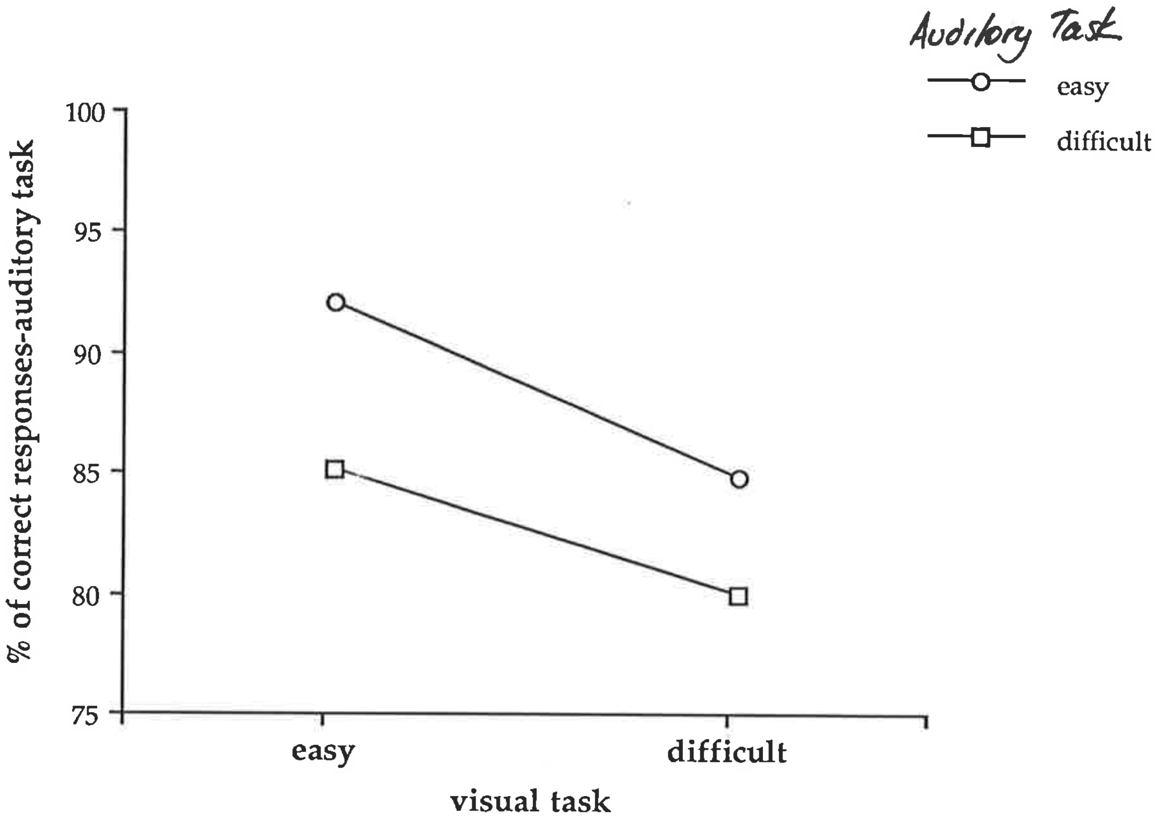


Figure 5.5. Mean percentage of correct responses for the 'easy' and 'difficult' auditory task performed concurrently with the 'easy' and 'difficult' visual task.

indicated that they used a strategy based on the discrimination of pattern density to assist with the discrimination of the 'difficult' visual task.

Responses to questions about dual-task performance showed a high degree of consistency. When asked how they performed the dual-task in the 'easy' condition, nine subjects indicated that they attended to the visual task before recalling the pattern of auditory tones from memory. The remaining three subjects adopted the opposite strategy - they reported attending to the auditory task first, and then switching attention to the visual task after they had decided on which auditory tone was presented. However, all 12 subjects reported adopting the same strategy when confronted with the visual patterned stimulus; namely, to 'attend' to the visual task before recalling the pattern of auditory tones from memory. None of the subjects involved in this study indicated that they were able to perform both tasks simultaneously.

Discussion

Problems associated with the accuracy of measures of perceptual performance previously discussed were clearly evident from the results of the present study. On the basis of target discriminations established in Session 1 using adaptive methods, subjects were expected to achieve, on average, about 80% correct responses for both the 'easy' visual and auditory single-tasks. However, the discrimination accuracy for these tasks varied considerably. The 'easy' visual task, for example, was performed particularly accurately, with nine of 12 subjects responding without error and the remaining three recording only one error in 24 trials. In contrast, the performance of the 'easy' auditory task was far more variable, with scores ranging from 46 to 100% correct. Nevertheless, the group mean of 84% correct responses for this task was not significantly different from the expected level of accuracy.

Performance of both 'difficult' tasks in the single-task condition was also quite variable. Scores for the 'difficult' visual task, for example, ranged from 46 to 96% correct, while those obtained for the 'difficult' auditory task ranged from 54 to 96% correct. The mean percentage of correct responses were also quite similar, with 83 and 82% for the visual and auditory tasks, respectively. Thus, while there was a significant difference between the performance of the 'easy' and 'difficult' visual tasks, there was no such difference between the two auditory tasks.

The reason for the dramatic improvement in 'easy' visual IT in the single-task condition, in particular, is unclear. This result is consistent with Kahneman's (1973) assertion that the capacity allocated to perform a task increases with the difficulty or complexity of a task as a result of changes in the level of arousal of the performer. However, there are also a number of other possible explanations for this result. Previous exposure to the 'difficult' visual task, for example, may have influenced the way subjects subsequently performed the 'easy' visual task. Although the use of strategies, such as the apparent movement effect were apparently minimized by the flash mask, a number of subjects reported using a similar strategy based on pattern density for the difficult task. Thus, it is possible subjects adopted the same type of strategy to simplify the discrimination of the 'easy' visual task. In other words, subjects simply used the 'pattern density cues' for the 'easy' task trials. It should be noted that these 'cues' are virtually the same as those previously described by subjects as 'changes in brightness'. There is some evidence to support this notion from the results of the questionnaire, in which five subjects reported using the same type of strategy for both the 'easy' and 'difficult' visual tasks. On the other hand, the improvement in performance may simply reflect changes that occur with practice, given the limited number of experimental trials in Session 1 from which the initial estimates were calculated.

A comparison of single and dual-task data indicated that there was no unambiguous support for either the single-channel or limited capacity model. According to the predictions of the single-channel model, for example, the performance of a 'second' task would be significantly worse in the dual-task than the single-task condition. However, in marked contrast to these predictions, both visual and auditory discriminations were performed equally well in the single and dual-task conditions. Moreover, both tasks showed a marginal (although not significant) improvement in discrimination accuracy under conditions in which at least one 'easy' task was involved. Similarly, the data were also not consistent with the predictions of a limited capacity model. While there was a significant difference between the 'easy' and 'difficult' tasks and also between the performance of the concurrent tasks, the task difficulty and single-task versus dual-task interaction predicted by the limited capacity model was not present. Nevertheless, it is evident from Figure 5.4 that performance of the 'difficult' visual task was marginally worse when the concurrent task was the 'difficult' rather than the 'easy' auditory task. However, the results of the planned comparison indicated that the interaction between level of difficulty of the task being performed and the concurrent task was not significant. Hence, it is evident that performance accuracy was virtually unaffected by the addition of a concurrent task, regardless of the level of difficulty of the second task. Therefore, the only model that is consistent with the empirical data obtained in this study is the type of multiple capacity model proposed by Navon and Gopher (1979).

Responses to the questionnaire given after the completion of the experimental task provided valuable information about how subjects rated each task, and also some important feedback about the techniques used to perform both single and dual-tasks. It is apparent from these answers that the majority of subjects believed the patterned visual task was the most difficult. Nevertheless, the experimental results indicated that subjects achieved about the same level of accuracy on both versions of the auditory task and the patterned visual task. Moreover, all subjects reported processing the concurrent tasks in 'sequence' rather than in parallel, by adopting a simple time-sharing strategy. Generally, this strategy involved initially attending to the visual signal before switching attention to the auditory task. However, not all subjects adopted this strategy under all conditions. For the dual-task involving the 'easy' visual stimulus, for example, a number of subjects initially attended to the auditory task before switching their attention to the visual task. But when confronted with the 'difficult' visual stimulus, all subjects reported adopting the former strategy. This suggests that the type of strategy adopted was influenced, at least to some extent, by the perceived difficulty of the tasks involved. Thus, it seems that subjects chose to perform the task perceived to be the most difficult first.

Nevertheless, the affects of auditory persistence, identified as an important methodological problem in the previous dual-task study was still evident. Responses to the questionnaire indicated that all 12 subjects were able to successfully recall the pattern of auditory tones from memory well after the physical stimulus had ceased. Thus, while the experimental results indicated that these two tasks can be performed at the same time, the results of the questionnaire suggest that processing is actually sequential, aided to a large extent by the persistence of the auditory signal.

Chapter 6

Summary and conclusions

6.1 Summary

This thesis has sought to examine the way in which concurrent signals are processed and, by so doing, determine whether the central decision mechanism deals with both signals at the same time, or whether one signal must be processed, either partially or completely, before a second signal can be dealt with. The framework for the analysis of dual-task performance was an independent decisions model. Based on single-task response accuracy, the independent decisions model predicted the level of performance expected for concurrent tasks, depending on whether each task was processed one at a time in sequence, or whether they were both processed at the same time, in parallel. However, before an accurate assessment of dual-task performance was attempted, some preliminary issues were addressed concerning the way in which subjects discriminate visual and auditory targets. In particular, two new visual backward masking techniques were tested to determine if either mask successfully limited the effectiveness of a strategy based on apparent movement, typically used to evade the masking procedure. Dual-task performance was subsequently tested using an IT target overlaid by one of the new visual masking techniques presented concurrently with an auditory tone discrimination task.

Analysis of the initial set of dual-task data for conformance with the parallel processing or single-channel predictions derived from the independent decisions model failed to clarify whether simultaneously presented signals were processed concurrently or sequentially, essentially because the performance of at least one of the two tasks was significantly better in the dual-task condition than the single-task condition. This was particularly evident when the dual-task data were grouped in terms of 'preferred' and 'non-preferred' tasks. The accuracy achieved on the 'preferred' task in the difficult condition, for example, was significantly better than the predicted 85% correct, with a mean of 89% correct responses. On the other hand, the level of accuracy achieved on the 'non-preferred' task was significantly less than predicted, with a mean of 74% correct responses. While this outcome was not consistent with the single-channel predictions of the independent decisions model, it does indicate that the concurrent presentation of visual and auditory signals results in some degree of processing interference.

Further support for the view that concurrent signals are processed in sequence came from the responses which individual subjects had made to a questionnaire eliciting information about single and dual-task performance. When questioned about how they performed the concurrent task, all subjects indicated that they dealt with each signal in turn, essentially on a time-sharing basis. Nevertheless, the fact that subjects were able to perform at least one of the two tasks significantly better in the dual-task condition than in the single-task condition indicated that there were some significant methodological issues that should be addressed. In particular, it was argued that the outcome of this study could be attributed, at least in part, to one of two factors; either, failure of the auditory backward masking stimulus to control the duration of the auditory target; or alternatively, unreliable or inaccurate initial estimates of single-task performance.

In an attempt to overcome the problems associated with the dual-task study, a new method for the presentation of both visual and auditory stimuli was devised. Rather than present the target stimulus for a variable period of time, a procedure was designed that used a fixed target duration and included a variable 'blank' or 'silent' ISI for the visual and auditory tasks, respectively. The results of a detailed study of the visual procedure, involving the presentation of the IT target stimulus for periods ranging from 10 to 25 ms, indicated that performance accuracy varied significantly as a result of changes in the stimulus duration and with the magnitude of the ISI between target offset and mask onset. Nevertheless, the results obtained for stimulus durations greater than 20 ms were compatible with those from previous IT studies, confirming that the revised task was measuring essentially the same visual processes.

Two additional experiments were carried out to refine further the methodology used for both visual and auditory presentations. Experiment 5 addressed two aspects of the revised auditory discrimination task; firstly, the effect of a background of 'white noise' on discrimination accuracy; and secondly, the test-retest reliability of the auditory task. The results indicated that 'white noise' at a level of intensity less than the target tone did not substantially increase the level of difficulty of the auditory discrimination. Nevertheless, the results did show that test-retest scores for repeated measures of the auditory task involving a 'silent' ISI were highly consistent. However, the results of the second study, Experiment 6, were cause for some concern. This experiment assessed the degree of consistency between the results of two psychophysical procedures; the adaptive staircase method proposed by Wetherill and Levitt, and analysis by the maximum likelihood statistic, Probit. Analysis of the two sets of data indicated that there were significant differences between the magnitude of the estimates of IT and ATD obtained by each method. However, from the analysis, it was impossible to determine which of the alternative procedures provided the best estimate of sensory discrimination. The extent to which the accuracy of single-task estimates effects the assessment of the dual-task performance is evident from the nature of the independent decisions model. The implicit assumption of this model is that the baseline data (in this case single-task measures of visual and auditory sensory discrimination) accurately reflect the 'true' ability of the performer. In other words, it is assumed that on average an individual will, over a series of repeated trials, perform a discrimination task at the level of accuracy predicted from the results of the initial single-task trials. However, it is apparent from the results of previous IT and ATD studies that the 'precision' required to assess accurately the predictions of an independent decisions model is not compatible with the accuracy of the estimates of single-task performance typically obtained using conventional psychophysical procedures.

An alternative plan was adopted for the last dual-task study, Experiment 7. Rather than relying exclusively on the estimates of single-task performance obtained using an adaptive psychophysical method, a block of 24 single-task trials for each experimental condition was given prior to the dual-task trials. The error scores resulting from these blocks were assumed to be indicative of single-task performance and, as a consequence, a suitable baseline measure for the assessment of the way concurrent tasks are processed. This change was intended to eliminate the effects of uncontrolled variables. Since the dual-task trials followed immediately after the final single-task trials, it was assumed that the effects of practice and the possible development of different strategies would be minimized. Further, a second version of each task was devised as a 'difficult' alternative to the standard task. These tasks were subsequently used to determine whether changes in the complexity of the two tasks affected dual-task performance in a manner consistent with the predictions of either a limited capacity model, a single-channel model or a multiple capacity model.

The outcome of this final dual-task experiment again failed to provide unequivocal support for either of the information processing models considered. Nevertheless, the results were, in many ways, consistent with those obtained in the previous dual-task study. For example, one of the two tasks was typically performed very accurately, much more accurately than would be expected on the basis of single-task performance. However, in contrast to the previous dual-task study, the 'easy' visual task was the one that was performed best, with the majority of subjects achieving greater than 95% correct responses. Further, it was also evident from the responses given to the questionnaire that a time-sharing strategy was used for both 'easy' and 'difficult' combinations of the two tasks throughout the dual-task trials.

6.2 *Conclusions*

The results of the experiments in this thesis have important implications for our understanding of the way in which information is processed. However, before discussing these implications in detail, there are a number of other issues that have a significant bearing on the information processing concept which must be clarified. The first issue concerns the selection of data, and the way it is organised into meaningful categories. This issue has an important bearing on the way simple perceptual problems are solved because the selection and organizing 'skills' form the basis for the development of cognitive strategies. Further, a cognitive strategy of one form or another is widely used to solve simple perceptual problems like those confronting subject's completing tasks estimating IT and ATD. Moreover, it has been suggested that the use of strategies as an aid to problem solving is a important characteristic of intelligent behaviour.

Visual discrimination tasks, like IT, which use a backward masking technique to control the duration of the target stimulus, are apparently susceptible to a particular type of strategy. This involves the use of subtle movement cues that result from the apparent extension of the short line of the target stimulus that occurs at the onset of the masking stimulus. However, the use of an alternative strategy was consistently reported in Experiment 7, particularly for the difficult visual task. Rather than perceiving movement, this strategy involved discriminating subtle differences in contrast at the onset of the mask. Thus, subjects perceived the area adjacent to the short line of the target stimulus as 'brighter' than the corresponding area adjacent to the long line. The widespread use of this strategy for the 'difficult' visual task suggests that the difference in contrast due to pattern density was readily apparent and may have significantly influenced the way subjects subsequently performed the 'easy' visual task. Thus, strategies which were developed during the initial learning phase were subsequently used by more than 50% of the subjects to discriminate accurately the position of the vertical line in the visual IT target at very short stimulus exposures.

There were also a number of different strategies reported for the auditory task. For example, several subjects reported attempting to listen only to the first (target) tone and then to attenuate the second (masking) tone. However, the results obtained by subjects who used this type of strategy indicated that this approach was not very effective. A more commonly used strategy involved the perception of a shift in frequency from the target to the masking tone; that is, by perceiving a difference in the pattern that occurs between the presentation of a *low tone and mask* and a *high tone and mask*. One subject described the two patterns as 'increasing' and 'decreasing' in frequency, respectively. However, what appeared to be a more effective strategy involved perceiving the target and masking tone as a unit of sound with its own distinct pattern. For instance, a number of subjects described the high tone and mask combination as 'sharp' and the low tone and mask as 'flat' or 'dull'. Thus, it would appear that these subjects responded to the additive result of the combined tones rather than to the target tone itself.

It was also evident from the responses to questions about the dual-task that subjects commonly used a simple strategy to deal with concurrent stimuli; a strategy based on performing each task in sequence essentially on a time-sharing basis. However, the application of the strategy varied somewhat between the two dual-task studies. In the first study, for example, a number of subjects attempted to make a decision about the auditory stimulus first, before dealing with the visual target. In fact, some subjects reported using the strategy based on listening only to the first of the auditory tones and switching attention to the visual stimulus prior to the onset of the second masking tone. However, none of the subjects who used this form of strategy was able to perform both tasks accurately in the dual-task condition; a result which indicates that this type of strategy was not very effective. Therefore, not surprisingly, the majority of subjects performed the dual-task in the opposite manner, initially attending to the visual stimulus and recovering the pattern of auditory tones from memory after a decision about the visual target had been made. Although the same two versions of the time-sharing strategy were used in the second dual-task study, only the form involving the recovery of auditory information from memory was used for trials involving the patterned visual stimulus. Moreover, the results obtained from the two dual-task studies indicated that this form of sequential strategy was by far the most effective.

The second issue concerns the nature of the auditory backward masking function and its effect on the persistence of auditory tones. Generally, the results of both dual-task studies and the responses to the questionnaire indicated that the auditory backward recognition masking procedure did not control the persistence of the auditory tone as effectively as the visual backward mask controlled the exposure of the visual target. Apparently, the reason for the failure of the auditory masking procedure lies with the operation of the auditory sensory processing mechanism. In contrast to the function of the visual backward masking stimulus, which effectively stops further processing of the visual target by erasing the image on the retina, the auditory mechanism appears to integrate the auditory target and masking tones without any significant degree of interference between the two. As a result, information about the auditory target is available well after the onset of the masking tone. While this result invariably reflects underlying differences in the nature of the visual and auditory sensory mechanisms, respectively, the persistence of auditory 'stimulation' made it virtually impossible to assess whether two signals can be processed at the same time on the basis of the error scores, because it failed to force subjects to process both tasks within the same timeframe.

An issue that also warrants further consideration is the relationship between the nature of the discrimination tasks and the type of dual-task strategy typically adopted. Previously, it was suggested that the persistence of the auditory signal significantly influenced the development of the time-sharing or sequential processing strategy typically used. At the outset of each dual-task study, subjects were quite apprehensive about whether they would be able to perform the dual-task satisfactorily, many initially believing that it would be virtually impossible to perform both tasks accurately. However, it was apparent from the way in which the dual-task was performed that many subjects were quick to recognise and use the persistence of the auditory signal to advantage, by adopting a strategy which involved initially attending to the visual target before accessing the more durable auditory signals from the 'echoic' store. Thus, recognition that the auditory signal was not as effectively masked, and was therefore much more durable than the visual signal, almost certainly led to the use of a sequential strategy. Moreover, the use of this strategy probably alleviated the need for subjects to perform both tasks at the same time.

Nevertheless, one of the main reasons for the wide range of results, particularly for the initial dual-task study, was that not all subjects adopted the same strategy. A small number of subjects, for instance, apparently failed to recognize the persistence of the auditory tones and attempted to use an alternative dual-task strategy. From the responses to the questionnaire, it seems that these subjects were influenced more by the difficulty of the two tasks than by any other factor, since they generally reported adopting a strategy based on performing the most difficult task first. Additionally, it is interesting to note that the subjects who attempted to use this strategy also reported finding the auditory task the most difficult. Typically, this group of subjects were unable to perform both tasks as accurately as those who adopted the former strategy. Nevertheless, the fact that they still tried, albeit unsuccessfully, to perform the two tasks in sequence adds considerable weight to the contention that concurrent visual and auditory tasks cannot be performed at the same time.

6.3 *Implications of the study*

At this point, it is necessary to digress briefly to review some important aspects of information processing theory relevant to the present study, before considering some further implications of these results. Recall from the introductory discussion that information processing theory assumes that input from the external environment is analysed through a series of processing stages, culminating in a decision and response. Thus, the information processing mechanism links the perception of the environmental input to an action via a series of processing stages. Further, it is clear from this discussion that most information processing models are quite similar, in as much as they all tend to postulate the same types of processing stages and mechanisms.

The limited capacity model proposed by Broadbent, for instance, consisted of four main stages; a sensory receptor stage which receives input from the environment, a short-term storage device capable of holding input data for a brief period of time; a selective filter mechanism which either selects or attenuates incoming data and a limited capacity decision mechanism which interacts with a response mechanism that controls the execution of motor skills. The single-channel model proposed by Welford consisted of essentially the same stages, although it was slightly more elaborate in that a number of interactive processes were postulated and assigned to specific anatomical locations. Nevertheless, the crucial difference between these and other information processing models concerned the operation of the central processing or decision mechanism, and in particular, the way data are handled during this stage of processing.

Several aspects of the present study have important implications for the way in which we view decision processes within the central processing mechanism. The most important aspect concerns the specific nature of the decision process, and in particular, whether two unrelated decisions can be made at the same time. Although analysis of the data obtained in the initial dual-task study failed to resolve unequivocally the issue of sequential versus parallel processing, two other sources of information support the assertion that decisions are made in sequence, essentially via a single-channel type mechanism. Firstly, analysis of the dual-task data in terms of 'preferred' and 'non-preferred' tasks, rather than by mode of presentation, indicated that the processing of one task interfered with the processing of the second task. In other words, the processing of the signal that subjects chose to attend to initially interfered with the processing of the second signal. While this result can be explained by assuming that there was insufficient capacity to perform both tasks at the same time in accordance with a limited capacity model, it does not in any way rule out processing by a single-channel mechanism. However, the strongest support for this type of processing mechanism came from the responses given to questions about the way in which the two tasks were processed in the dual-task condition. The responses to the questionnaire unanimously indicated that all subjects who attempted the dual-task processed the concurrent visual and auditory signals in sequence. Moreover, none of the subjects involved in either dual-task study reported that they were able to attend to, or discriminate the concurrent task in the same timeframe. Thus, from these two results together, it was clear that decision processes could be best described by a single-channel mechanism.

It is also clear from the results of this study that all conscious decisions about visual and auditory stimuli are taken through a common central processor, rather than each modality having its own unique decision mechanism. This conclusion follows from our knowledge of the central nervous system, which implies that stimuli from different peripheral sensory mechanisms are transmitted along different neural pathways to a decision mechanism. According to this logic, the first common processing stage for signals in different modalities would be the decision stage. The need for co-ordinated behaviour requires that subsequent stages of processing, such as response selection, must also be common to all peripheral sensory input. However, since the visual and auditory discrimination tasks used in this study do not involve complex responses, it follows that distinct visual and auditory signals will only interact if they both require access to the same decision mechanism. Hence, the observed interference between the performance of the 'preferred' and 'non-preferred' tasks is consistent with the assertion that visual and auditory signals are processed through a common mechanism.

A further implication from the results of this study concerns the selection of data for further processing, and in particular, whether selection takes place at an early or late stage of processing. According to the responses given in the questionnaire, the selection of data for further processing was entirely under the control of the subject. At the time when stimuli were presented, one of the concurrent signals was selected for immediate processing, the other being 'held in store' until the processing mechanism was free to accept it. Thus, either the visual or the auditory target was initially selected for processing, the choice about which one to deal with first depending on the type of strategy the subject adopted.

Moreover, the selection process can also occur at a more fundamental level. The results of the IT and ATD experiments, for instance, indicated that subjects often based their decisions on critical aspects of the target and mask presentation, rather than on a detailed analysis of the target itself. These critical aspects are those previously alluded to; features such as subtle changes in the contrast and brightness of the visual display, or the 'dull' or 'sharp' nature of the integrated target and masking tones of the auditory presentation. These results imply that the selection of data takes place early in the processing stage, rather than late, since the features of the visual target frequently selected are not part of the 'literal image' as such; rather they are an illusory representation of the transition from target to mask that is probably not accessible at later stages of processing. Further, it is apparent that subjects actively seek out specific aspects of both visual and auditory presentations, rather than passively processing all data associated with stimuli. Moreover, there is no evidence to suggest that further processing of either signal was required. Thus, a two-stage model, such as that proposed by Duncan (1980) would not seem to be appropriate for the type of tasks used in this study.

On the other hand, the results of the dual-task studies in particular, would appear broadly to support the type of processing mechanism proposed by both Pashler (1989) and McCann & Johnston (1992). In the present study, it was apparent that a decision (or the selection of a response) for the second target stimulus was delayed (or postponed) until a decision about the appropriate response to the first target stimulus was selected. This interpretation, which suggests that a processing 'bottleneck' occurs at the decision stage, is consistent with McCann and Johnston's assertion that there is a 'central bottleneck' somewhere between stimulus encoding and response initiation.

Furthermore, in contrast to White's (1993) assertion that IT does not involve post-sensory or early cognitive processing, the results of this study indicate that both simple and complex tasks involve a substantial cognitive component; a component that requires the application of specific knowledge about the nature of the task that can be effectively used to simplify the discrimination process. Thus, simple perceptual tasks such as IT and ATD, for instance, are not necessarily discriminated using explicit information about the target stimulus; instead, practiced subjects tend to perform these tasks by applying cognitive strategies derived from consistent features that occur at target presentation. In the case of the IT task, it seems that subjects frequently associate specific features of the visual display with a particular outcome and hence quickly learn to discriminate the target signal on the basis of these features. This process may also involve a certain amount of deductive reasoning on the part of the subject. For example, from the perception of movement at the onset of the mask, it may be inferred that the effect is due to the apparent extension of the short line, rather than the long line. The application of a general plan or strategy is also evident for dual-task performance. And although the choice of strategies for this task was more restricted, it was still evident that the successful performance of complex tasks depends, to a large extent, on the ability of the subject to develop and use appropriate strategies.

The results of the dual-task studies, particularly those obtained in Experiment 7, could also be interpreted as support for a channel of 'unlimited' capacity, similar to that proposed by Moray (1967). Concurrent performance of the 'easy' visual and auditory tasks, for example, was consistently better than the performance of the same tasks in the single-task condition. Similarly, the performance of the 'easy' visual task together with the 'difficult' auditory task was also better in the dual than the single-task condition. Both of these results are consistent with the idea of 'unlimited' capacity. However, given the outcome of the questionnaire together with the widespread use of 'cognitive strategies' to simplify the discrimination tasks, a more plausible explanation is provided by the interpretation of concurrent processing as a 'skill'.

Advocates of the 'skills' approach, for instance, would argue that the performance of tasks, like IT, involve a significant 'skill' component; the 'skill' in this case being the use of cognitive strategies to simplify the discrimination. However, unlike the studies of Spelke *et al.* (1976) and Hirst *et al.* (1980), the cognitive skills used, particularly for the visual task apparently developed more or less spontaneously (although probably as a result previous experience), rather than through extended practice. Similarly, the type of time-sharing strategy generally used for the dual-task was seemingly chosen at the outset of the dual-task trials and virtually unaffected by further practice. However, this does not necessarily mean that performance of the dual-task would not improve as a result of additional practice.

Nevertheless, there are also aspects of this study that are clearly not consistent with the 'skills' approach, particularly the type of 'skills' model proposed by Hirst and Kalmar (1987). The results of both dual-task studies, for example, indicate that one of the two tasks was performed much more accurately that the second task. This is consistent with the idea that one task interfered with the performance of the other. However, as Hirst and Kalmar (1987) pointed out, interference or cross talk is not likely to occur for a combined visual and auditory tasks if there are 'parallel lines'. Therefore, according to Hirst and Kalmar's logic, the results of this study indicate that there are not 'parallel lines' and therefore the two tasks must have been processed through a 'single line', probably in sequence. In other words, at some stage, the processing of both tasks required access to the same 'single line' sequential processing mechanism.

There are also a number of wider implications that follow from the results of this study; implications that are broadly related to the biological development of the perceptual mechanism. The results indicate that a significant part of the problem with the assessment of dual-task performance was related to the effectiveness of the backward masking procedure. Generally, the effectiveness of a masking stimulus depends on the nature of the stimulus being masked, as well as on the characteristics of the mask. However, the design of the sensory mechanism also has a significant impact on whether or not a mask is effective in controlling the duration of the target stimulus. In this thesis, many of the difficulties encountered with the auditory masking technique can be directly related to the nature and design of the auditory sensory mechanism. This is clear from the contrast between the visual and auditory sensory mechanism and the type of signals each mechanism must process.

The visual system, for example, must reflect a rapidly changing environment; an environment in which the perception of movement is critical. Thus, the visual mechanism has evolved in a way that allows visual information to be continually upgraded in line with these changes. Images on the retina are transient, lasting for a brief interval before being replaced by a fresh image. As part of the normal operation of the visual system, the perception of sensory stimulation erases or overwrites the effects of previous stimulation. Therefore, the visual backward masking technique is simply an extension of the natural action of the visual processing mechanism under carefully controlled conditions. In contrast, auditory signals are only intelligible over a period of time. This was evident in Experiment 5, for example, where subjects found the discrimination of different frequency tones of duration less than 35 ms virtually impossible, regardless of the ISI between target offset and mask onset. Further, auditory signals are more durable in the sense that they can be 'held' in a working memory for a much longer period of time than is the case for visual signals. Thus, the auditory sensory mechanism has evolved in such a way that it is capable of holding the 'image' of auditory stimulation long enough to allow effective perceptual analysis to take place.

Additionally, the way in which the auditory sensory mechanism records different frequency stimulation also limits the effectiveness of the auditory backward masking procedure. Previous studies of audition indicate that tones of different frequencies activate specific receptors in separate areas of the auditory sensory mechanism (Butter, 1968). Therefore, a tone of a particular frequency cannot interfere with or erase a tone of a different frequency since each tone is 'physically' held in a separate location. As a result, the backward masking of one (target) tone by a subsequent (masking) tone, or for that matter, a white noise masker, does not necessarily interfere with, or stop further processing of the initial auditory target tone.

When considered from this perspective, it seems clear that each sensory processing mechanism has undergone significant biological development, probably through a process of evolution by natural selection, so that it can adequately receive and analyse a range of signals from the environment. As we have previously indicated, the visual processing mechanism has adapted so that it can register events, such as movement, in a rapidly changing environment. On the other hand, the processing requirements for auditory signals are different; to be coherent, auditory data must be integrated over a period of time. Thus, the auditory mechanism must be capable of holding the image of a tone for a much longer period of time. The decoding of language is a good example of the type of complex auditory processes that requires the integration of a number of signals and a range of frequencies over time.

It is also logical to assume that the phylogenetic development of the visual and auditory peripheral sensory mechanism has had a significant impact on the human information processing mechanism. From the way signals are handled at the receptor stage, it is evident the peripheral sensory mechanism acts as a short-term storage device, holding data for a sufficient period of time to compensate for the limitations of the human information processing mechanism. And since each particular sensory device is capable of holding data awaiting access to a central processing mechanism, the need for parallel processing of concurrent signals is virtually eliminated. Therefore, given the different temporal characteristics of each type of signal, it is clear that data presented in the visual and auditory modes at the same time can be simply dealt with in sequence, via a single-channel type mechanism, at least as effectively as it could if it were processed in parallel.

6.4 Some limitations of the study

As previously indicated, there are a number of limitations to the experiments in this thesis that make it particularly difficult to determine whether concurrent visual and auditory tasks were processed at the same time. These limitations are due to a number of factors that directly effect single-task performance and as a result, have an indirect effect on dual-task performance. One major limitation is the uncertainty surrounding the accuracy of single-task estimates of sensory discrimination obtained using an adaptive psychophysical method. This is an important issue because a reliable assessment of dual-task performance based on the predictions of an independent decisions model pre-supposes that accurate estimates of single-task performance can be obtained.

Serious doubts about the accuracy of point estimates of single-task performance in the present study were raised following analysis of the first dual-task study. The results of this study showed that performance of the auditory component of the dual-task was far better than in the single-task condition. It was subsequently argued that this result could be explained, at least partially, if the initial estimates of single-task performance were inaccurate or erroneous. Moreover, the difficulties when establishing accurate estimates of single-task performance were highlighted in another experiment that compared the magnitude of the estimates obtained by alternative procedures; one an adaptive staircase method; and the second, analysis of the same data using a maximum likelihood statistic.

Nonetheless, there are a number of problems other than those associated with the psychophysical procedures. Some of these also have an impact on the reliability of single-task estimates through the effect of uncontrolled variables. One aspect of sensory discrimination that was particularly difficult to control was the effect of practice; in other words, the improvement or learning that occurs with repeated performance of a task. Although sensory discrimination tasks, such as visual IT, are relatively simple, there is still a significant practice effect. Nevertheless, the difficulty arises not with the practice effect per se, but with the amount of practice required by different subjects to achieve asymptotic performance. Furthermore, it was virtually impossible to determine whether the level of performance achieved at any time would improve further as a result of practice or whether it would simply remain at the same level.

The amount of practice required to reach stable performance was also influenced by another factor; namely, the use of cognitive strategies. As we have already discussed, the process of learning to perform a task in a skilled manner involves the use of subtle 'cues' from which critical features of the target stimulus can be deduced. However, the difficulty that occurs when trying to limit the use of 'cues' is that subjects actively seek ways to simplify perceptual tasks. As a result, attempts to limit one particular type of strategy by changing one aspect of the task often leads to the development of different, but equally effective alternative strategies. This was evident from the attempt to change the complexity of the visual IT task by using a random visual noise pattern; a change that resulted in many subjects adopting a particularly effective strategy based on differences in contrast associated with the visual pattern adjacent to the short and long lines of the target stimulus. Moreover, the reliability of a particular result is confounded by the variability in the use of strategies. It is clear from this study, as well as from previous discrimination studies, that some subjects apparently develop effective strategies after relatively few practice trials, while others virtually never report using any type of sophisticated strategy at all.

The type of strategy typically used also effects skilled performance in another way. As strategies develop, the criterion on which decisions are made tend to change. A skilled performer, for example, may well respond with very high accuracy on the basis of a small amount of information. And as the performer becomes more experienced, the performance criterion apparently become better defined, with the operator focusing on specific sources of information about the target and attenuating other less critical information. Again, the problem is not so much that the performance criterion change over time, but the fact that it changes in an uncontrolled manner, with different subjects adopting a different performance criterion during different stages of a study. As we have previously indicated, changing performance criteria may well account for some aspects of the dual-task results.

Another facet of human behaviour that is also quite variable and difficult to control are fluctuations in the attention of the subject. Changes in attention occur not only over the course of an experimental session, but may also change substantially between sessions. As we have already discussed, the attentional factor can be particularly critical for studies that use adaptive psychophysical methods such as the PEST procedure, since small changes in the level of attention can have a significant effect on the magnitude of psychophysical estimates. However, it may also be a critical factor in dual-task performance. If Kantowitz and Knight's assertion that attention (or capacity) increases monotonically with the demands of a task is correct, then the 'attentional resources' available for a single-task would be substantially less than those available for dual-tasks. Moreover, certain aspects of the dual-task results were consistent with Kantowitz and Knight's notion. For example, the better-than-predicted level of accuracy in the dual-task condition could be explained by an increase in the 'attentional resources' available to perform the more demanding dual-task.

The issue of auditory backward masking, which was assumed to have a significant impact on the results of the dual-task study, also required further clarification. As we have already explained, one of the main problems that occurs when evaluating dual-task performance is how to force subjects to process both signals during the same timeframe. To achieve this objective, the exposure of each target stimulus was assumed to be controlled by a backward masking stimulus. In fact, much of the initial experimental work was aimed at developing an effective visual backward masking procedure. Nevertheless, one of the main limitations of both dual-task studies proved to be the difficulty when masking auditory tones. A number of issues relating to the auditory task were addressed in Experiment 6. However, from the results of this study, it was not possible to draw firm conclusions about whether or not the auditory backward masking stimulus effectively stopped further processing of the target tone. Previous studies which used a similar experimental procedure indicated that pure tones could be effectively masked by the subsequent presentation of tones of different frequency. The effectiveness of the auditory masking procedure could have been established by adopting a slight modification to the format of Experiment 6. For example, if the application of a second tone does not mask the first tone, the duration of the ISI between the offset of the first tone and the onset of the second would not affect performance. In other words, performance would be purely a function of the stimulus duration; the ISI between target offset and mask onset being virtually irrelevant. Thus, by holding the stimulus duration constant (at say 35 or 50 ms) and varying the ISI over three or four values, the effectiveness of the auditory backward recognition masking stimulus could have been established.

6.5 *Directions for future research*

From the results of this study, it is apparent that further work is required to resolve the nature of concurrent performance. Moreover, it is problematical whether the high level of accuracy required for the independent decisions model can be achieved with the currently available technology. Therefore, future studies looking at the question of concurrent processing should attempt to assess differences in error scores as the complexity of the task changes rather than test the predictions of an independent decisions model, mainly because of the errors associated with single-task performance. An acceptable format for a dual-task study which entails an initial single-task estimate as a baseline measure of performance would be similar to that used in the second dual-task study (Experiment 7). In that study, single-task practice and performance were conducted in the first session, while the baseline estimates of single-task performance were established from a block of trials at the start of the second session. Following the single-task block, subjects attempted the dual-task blocks. This type of format would at least minimize the effects of practice and also increase the likelihood that the same type of strategy was used for each task in the single and dual-task conditions.

Nevertheless, if dual-task processing requirements are to be evaluated by manipulating task difficulty, it is important that the 'easy' and 'difficult' variants are performed in a similar manner, preferably by using essentially the same type of strategy. To satisfy this requirement, the type of information available from each variant of a particular task must be basically the same. In other words, the type of cues available should be the same for both the 'easy' and 'difficult' versions of the discrimination task. A difficult version of the visual task, for example, might be developed by reducing the difference in the line length of the IT target to 5 mm, rather than the 10 mm difference used for the traditional IT target. Thus, rather than 25 and 35 mm line lengths for the short and long line, respectively, the lengths of the difficult variant would be revised to 27.5 and 32.5 mm, respectively. While this revision would be expected to make target discrimination more difficult, the task would still maintain the same basic characteristics of the traditional IT task and hence minimize the use of alternative strategies.

On the other hand, the auditory task requires substantial revision. The results of the dual-task study indicated that it was virtually impossible to mask auditory tones by either white noise or by a tone of different frequency. A suitable alternative auditory procedure might be developed using a pattern of auditory tones as the target stimulus, rather than a single tone as used in the present experiments. For example, a simple alternative discrimination task may involve a series of long and short tones, followed by a suitable masking stimulus. The objective for this type of task would be to discriminate which pattern of tones was presented, rather than whether the target tone was of high or low frequency. To increase the complexity of the auditory task, the respective durations of the long and short tones could be changed so that the temporal difference between each of the tones decreased. But regardless of the type of auditory task used, a substantial amount of preliminary work is required to develop a specific task suitable for assessing dual-task performance.

Finally, there are two aspects of the present study which have an impact on the learning process, and in particular, the way in which training is conducted. The first concerns the use of strategies. The present results have indicated that even the most elementary tasks involve some form of strategy. Thus, if performance is to be maintained at a level appropriate to the requirements of a specific task, where possible, the operator should be encouraged to use strategies that will be effective. Moreover, as part of the training program, the nature and effectiveness of specific types of strategies may need to be discussed so that the benefits and pitfalls of performing a task in a certain way can be highlighted. Further, in the initial stage, operators should be given sufficient practice of a critical nature so that they can confidently perform the required task at the appropriate level. Additionally, given that skilled operators tend to concentrate on certain features of a task while ignoring other less relevant features, care should be taken, particularly during the initial training phase, to make sure that the operator attends to the correct features of the task. Failure to provide adequate training may not adversely effect the performance of routine tasks, but it may be a crucial factor in more critical tasks.

The second aspect of this study concerns the criteria on which performance are based. It is apparent that consistent and reliable performance can only be maintained if the criteria on which it is based are also relatively constant. For example, under normal circumstances, operators may perform a task at the required level of accuracy, even though performance is based on different criteria. Nevertheless, under more stringent conditions, it may be critical that the same performance criteria are maintained. Again, to ensure that adequate levels of performance are achieved, the minimum performance criteria should be established at the outset. To a certain extent, the nature of the task involved and the penalty associated with an incorrect decision will dictate the performance criteria that are acceptable.

List of Appendices.

Appendix 2.3.

Estimates of IT(ms at 85% correct) from Experiment 1 for two masking procedures and orders of presentation. Subjects in Condition 1 performed the tasks involving the pi-figure mask first followed by the two-stage mask; Condition 2 was in the reverse order.

two-stage mask	pi-figure mask
Condition 1	
57	50
20	35
44	72
62	51
21	82
33	53
19	27
Condition 2	
93	98
19	44
61	62
33	66
41	52

Appendix 2.4.

Analysis of estimates of IT from Experiment 1 obtained under two masking procedures (Mask) and orders of presentation (Condition).

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Main Effects					
Condition	866.20	1	866.20	1.89	0.185
Mask	1427.41	1	1427.41	3.11	0.093
Interactions					
Condition x Mask	2.41	1	2.41	0.01	0.943
Within + Residual	9178.97	20	458.95		
Model	2356.99	3	785.66	1.71	0.197
Total	11535.96	23			

Appendix 2.5.

Estimates of IT(ms at 85% correct) from Experiment 2 for two masking procedures and orders of presentation. Subjects in Condition 1 performed the task involving the flash mask first, followed by the pi-figure mask. Condition 2 was in the reverse order.

Condition 1	
flash mask	pi-figure mask
85	73
101	75
102	95
109	89
69	69
81	90
136	73
57	39
91	71
Condition 2	
83	61
122	110
104	78
107	85
65	55
128	96
79	23
102	72
128	91
52	36

Appendix 2.6.

Analysis of estimates of IT from Experiment 2 under two masking procedures (Mask) and orders of presentation (Condition).

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Main Effects	4532.70	2	2266.35	3.96	0.029
Condition	0.54	1	0.54	0.001	0.976
Mask	4532.15	1	4532.15	7.91	0.010
Interactions					
Condition x Mask	185.73	1	185.73	0.32	0.516
Residual	19472.99	34	572.74		
Total	24301.37	37			

Appendix 2.7.

Analysis of estimates of IT from Experiment 2 under two masking procedures (Mask) for strategy users and non-users.

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Main Effects	5809.35	2	2904.67	5.35	0.010
Mask	5734.75	1	5734.75	10.55	0.003
Strategy	757.87	1	757.87	1.39	0.246
Interactions					
Mask x Strategy	783.20	1	783.20	1.44	0.238
Residual	18477.71	34	543.46		
Total	24301.37	37			

Appendix 2.8.

Correlation coefficients obtained in Experiment 3 for WAIS IQ and IT scores for 'cue users' and 'nonusers' and the total sample for two masking conditions.

'cue users' for pi-figure mask

(n = 8)

	IT(1)	IT(2)	VIQ	PIQ
IT(1)	1.0000			
IT(2)	#	1.0000		
VIQ	#	-0.5408	1.0000	
PIQ	#	-0.6619	0.5354	1.0000
FIQ	#	-0.6487	0.9407*	0.7537

'nonusers' for pi-figure mask

(n = 9)

	IT(1)	IT(2)	VIQ	PIQ
IT(1)	1.0000			
IT(2)	#	1.0000		
VIQ	#	0.2586	1.0000	
PIQ	#	-0.6125	-0.2727	1.0000
FIQ	#	-0.3358	0.5711	0.6262

'nonusers' for flash mask

(n = 15)

	IT(1)	IT(2)	VIQ	PIQ
IT(1)	1.0000			
IT(2)	#	1.0000		
VIQ	-0. 2704	#	1.0000	
PIQ	-0.7628*	#	0.3177	1.0000
FIQ	-0.5292*	#	0.9251*	0.6309*

Total sample

(n = 17)

	IT(1)	IT(2)	VIQ	PIQ
IT(1)	1.0000			
IT(2)	0.7218*	1.0000		
VIQ	-0.2102	-0.2368	1.0000	
PIQ	-0.6546*	-0.6087*	0.3418	1.0000
FIQ	-0.4266	-0.4439	0.9077	0.6812*

Note! IT(1) used the flash mask and IT(2) used the pi-figure mask.

Appendix 3.3.

Dual-task data consisting of the number of responses in each category from Experiment 3 for 'easy' and 'difficult' conditions.

Easy condition - 90% level.

1. Significant χ^2: data not consistent with the Ho.

Subj.	a	b+c	d	n	χ^2(2 d.f.)	Associated prob.
S3	17	13	2		20.99	<0.005
S4	19	13	0		11.27	<0.005
S11	19	13	0		11.27	<0.005
S12	19	11	2		15.43	<0.005
Σ	74	50	4	128		

2. Non-significant χ^2: data consistent with the Ho.

Subj.	a	b+c	d	n	χ^2(2 d.f.)	Associated prob.
S1	26	6	0		0.3302	>0.05
S2	27	5	0		0.4653	>0.05
S5	29	3	0		2.0085	>0.05
S6	26	5	1		1.5455	>0.05
S7	28	4	0		1.0247	>0.05
S8	28	4	0		1.0247	>0.05
S9	25	7	0		0.6196	>0.05
S10	28	4	0		1.0247	>0.05
S13	29	3	0		2.0085	>0.05
S14	22	10	0		4.0340	>0.05
Σ	268	51	1	320		

Difficult condition - 85% level.

3. Significant χ^2 :data not consistent with the Ho.

Subj.	a	b+c	d	n	χ^2(2 d.f.)	Associated prob.
S3	50	34	12		53.9327	<0.005
S4	53	41	2		15.0190	<0.005
S5	52	42	2		16.8957	<0.005
S7	82	13	1		8.3100	<0.02
S11	40	46	10		59.8023	<0.005
S12	52	43	1		38.1947	<0.005
S14	57	38	1		10.2925	<0.01
Σ	386	257	29	672		

4. Non-significant χ^2 :data consistent with the Ho.

Subj.	a	b+c	d	n	χ^2(2 d.f.)	Associated prob.
S1	73	18	5		5.6404	>0.05
S2	63	31	2		2.3316	>0.05
S6	65	29	2		1.1205	>0.05
S8	71	22	3		0.6167	>0.05
S9	80	15	1		5.9263	>0.05
S10	71	24	1		0.6712	>0.05
S13	69	24	3		0.3379	>0.05
Σ	492	163	17	672		

Appendix 3.4.

Percentage of correct responses from Experiment 3 for the preferred and non-preferred tasks for two conditions. There were 32 trials per subject for the 'difficult' condition and 96 trials for the 'easy' condition.

	Condition			
	'difficult'		'easy'	
	auditory task	visual task	auditory task	visual task
Parallel processing				
	0.875	0.938	0.833	0.875
	0.875	0.969	0.792	0.896
	1.000	0.906	0.885	0.771
	0.906	0.875	0.927	0.781
	0.938	0.938	0.969	0.854
	0.938	0.938	0.969	0.760
	0.938	0.844	0.896	0.792
	1.000	0.875		
	0.969	0.938		
	1.000	0.688		
Other				
			0.615	0.782
			0.708	0.823
			0.979	0.542
	0.625	0.844	0.906	0.677
	0.656	0.938	0.958	0.885
	0.906	0.688	0.760	0.562
	0.750	0.781	0.844	0.688

Appendix 3.5.

Analysis of percentage of correct auditory responses from Experiment 3 by strategy and task.

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Main Effects	0.293	2	0.147	6.19	0.007
Task	0.280	1	0.280	11.81	0.002
Strategy	0.000	1	0.000	0.01	0.934
Interactions					
Task x strategy	0.094	1	0.094	3.95	0.058
Explained	0.375	3	0.125	5.28	0.006
Residual	0.569	24	0.024		
Total	0.945	27			

Appendix 3.6.

Analysis of percentage of correct visual responses from Experiment 3 by strategy and task.

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Main Effects	0.240	2	0.120	8.10	0.002
Task	0.109	1	0.109	7.38	0.012
Strategy	0.075	1	0.075	5.04	0.934
Interactions					
Task x strategy	0.002	1	0.002	0.16	0.694
Explained	0.240	3	0.080	5.40	0.006
Residual	0.356	24	0.015		
Total	0.596	27			

Appendix 3.7.

Percentage of correct responses from Experiment 3 for the preferred and non-preferred tasks for 'difficult' and 'easy' conditions.

Condition			
'difficult'		'easy'	
preferred task	non-preferred task	preferred task	non-preferred task
0.875	0.938	0.833	0.875
0.969	0.875	0.896	0.792
0.844	0.625	0.781	0.615
0.938	0.656	0.823	0.708
1.000	0.906	0.979	0.542
0.906	0.875	0.885	0.771
0.938	0.938	0.958	0.885
0.938	0.938	0.927	0.781
0.938	0.844	0.969	0.854
1.000	0.875	0.969	0.760
0.906	0.688	0.760	0.552
0.750	0.781	0.844	0.688
0.969	0.938	0.896	0.792
1.000	0.688	0.906	0.677

The 'difficult' task consisted of one block of 32 trials; the 'easy' tasks consisted of three blocks of 32 trials.

Appendix 3.8.

Analysis of percentage of correct responses from Experiment 3 for preferred and non-preferred tasks (Task) and the easy-difficult conditions.

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Between subjects	0.2545	13	0.0196	3.76	0.01
Treatments	0.2922	3	0.0974	18.73	0.01
Task	0.2240	1	0.2240	43.08	0.01
Condition	0.0587	1	0.0587	11.28	0.01
Interactions					
Task x Condition	0.0095	1	0.0095	1.83	>0.05
Residual	0.2041	39	0.0052		
Total	0.7508	55			

Appendix 4.3

Experiment 4 session 1: Raw scores (number correct out of 16 trials) for two masking conditions at four SOAs under four ISIs.

	stimulus duration															
	10				15				20				25			
	ISI				ISI				ISI				ISI			
	20	40	60	80	20	40	60	80	20	40	60	80	20	40	60	80
Flash mask Subject																
1	8	9	7	7	9	7	12	7	5	7	6	9	6	7	13	10
3	9	8	7	7	8	7	13	12	11	11	14	14	11	13	16	14
5	8	10	8	10	8	9	11	5	7	7	9	11	9	11	13	12
7	8	8	11	11	8	9	10	15	8	12	11	12	10	13	15	15
9	6	7	10	14	8	8	14	15	8	15	15	16	9	14	15	16
11	9	7	7	9	10	9	8	9	11	8	11	10	10	11	13	13
13	5	8	6	9	4	9	11	10	9	12	12	11	6	11	14	14
15	6	7	10	9	8	9	15	15	12	12	13	16	9	11	15	16
17	7	6	8	11	7	6	8	7	7	5	7	8	10	11	8	9
19	8	8	10	15	13	12	16	14	11	16	15	16	15	15	16	16
21	5	7	5	4	10	6	7	6	9	6	10	9	9	11	6	9
23	8	10	8	7	7	6	6	6	4	9	7	9	9	10	9	11
Pi-figure mask																
2	11	11	7	8	7	10	8	9	10	6	10	11	7	8	12	11
4	6	7	6	8	6	9	6	9	5	7	6	10	6	8	7	9
6	9	9	9	6	8	8	10	10	9	9	9	7	9	8	8	15
8	6	5	8	8	10	8	10	7	4	9	7	10	8	7	12	11
10	9	10	7	5	9	6	8	7	10	10	12	11	10	13	13	13
12	7	11	7	8	10	11	8	8	7	7	12	9	9	11	9	11
14	8	9	6	8	5	6	3	8	10	5	9	9	9	8	5	7
16	8	8	9	9	7	7	8	5	2	8	12	10	7	7	11	13
18	8	10	8	9	9	10	12	12	4	10	10	12	8	14	14	16
20	5	4	6	7	6	8	11	5	11	8	7	5	13	4	7	8
22	10	5	8	10	9	11	6	10	9	7	13	8	9	10	12	13
24	10	10	8	15	10	10	8	7	10	10	9	8	10	5	9	10

Experiment 4 session 2: Raw scores (number correct out of 16 trials) for two masking conditions at four SOAs under four ISIs.

	stimulus duration															
	10				15				20				25			
	ISI				ISI				ISI				ISI			
	20	40	60	80	20	40	60	80	20	40	60	80	20	40	60	80
Pi-figure mask Subject																
1	8	7	10	12	8	8	13	11	7	5	13	12	9	14	11	12
3	8	7	13	10	8	11	13	16	11	13	14	16	14	15	15	16
5	8	7	7	10	11	10	11	9	7	12	9	12	10	11	8	12
7	10	9	8	6	12	10	7	12	10	9	11	15	11	14	16	15
9	7	4	10	13	12	10	15	16	8	14	16	16	14	16	16	16
11	8	8	11	7	11	9	12	8	9	9	9	12	6	10	14	13
13	10	10	11	8	7	10	12	14	12	14	14	16	14	16	15	16
15	10	10	12	10	7	9	15	13	13	15	15	16	13	15	15	16
17	8	6	7	13	9	9	9	7	12	6	11	10	11	9	12	10
19	9	8	15	13	12	16	16	15	15	16	16	16	16	16	16	16
21	10	7	4	11	13	9	7	10	5	10	8	10	11	12	12	14
23	7	11	10	9	8	8	9	8	10	5	10	7	10	11	10	11
Flash mask																
2	7	9	10	6	13	9	7	9	5	6	13	6	7	10	14	10
4	6	10	8	10	9	8	7	9	8	9	7	8	11	14	5	6
6	6	13	7	10	11	7	7	12	6	8	9	11	10	9	15	13
8	10	4	8	11	4	6	6	4	5	6	10	6	3	5	11	10
10	8	11	9	9	8	6	9	10	10	7	11	15	10	11	14	12
12	10	9	8	11	12	8	9	8	6	13	10	12	8	12	12	14
14	6	8	6	3	8	9	9	8	9	6	12	7	7	8	9	5
16	9	7	7	8	9	9	9	10	5	9	13	15	9	12	15	16
18	8	5	7	9	10	9	10	14	12	10	11	16	11	12	16	14
20	8	7	8	12	12	5	9	9	5	6	10	9	7	7	6	7
22	10	10	13	5	9	9	9	9	9	9	11	10	10	12	13	11
24	8	10	7	8	11	6	8	8	9	6	11	8	9	10	9	8

Appendix 4.4.

The percentage of correct responses from Experiment 4 at each of four stimulus durations and ISIs for two orders of presentation and type of backward mask. An * indicates that the mean percentage of correct responses was significantly greater than expected by chance, where chance level was 50% correct.

	Order 1				Order 2			
	flash mask				pi-figure mask			
	stimulus duration				stimulus duration			
	10	15	20	25	10	15	20	25
ISI								
20	45	52	53	59**	51	50	47	55
40	50	51	61**	72**	52	54	50	54
60	51	69**	68**	80**	46	51	60**	62**
80	59**	63**	73**	81**	53	51	57*	71**
	pi-figure mask				flash mask			
	stimulus duration				stimulus duration			
	10	15	20	25	10	15	20	25
ISI								
20	54	61**	62**	72**	50	60**	46	53
40	49	62**	67**	83**	54	47	49	64**
60	61**	72**	76**	83**	51	52	67**	72**
80	64**	72**	82**	87**	53	57*	64**	66**

* 95% CI for 50% chance level performance 43% < μ < 57%.
** 99% CI for 50% chance level performance 41% < μ < 59%.

Appendix 4.5.

Analysis of the percentage of correct responses from Experiment 4 by stimulus duration and ISI.

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Condition	507.0	1	507.00	7.27	0.013
Within cells	1534.87	22	69.77		
Linear	317.19	1	317.19	26.97	0.000
Condition by Linear	38.13	1	38.13	3.24	0.086
Within cell	176.41	22	11.76		
Quadratic	24.79	1	24.79	7.16	0.014
Condition x Quadratic	0.54	1	0.54	0.16	0.696
Within cell	76.19	22	3.46		
Cubic	77.29	1	77.29	10.64	0.004
Condition x Cubic	7.11	1	7.11	0.98	0.333
Within cell	159.76	22	7.26		
Mask	130.02	1	130.02	20.62	0.000
Condition x Mask	30.88	1	30.88	4.90	0.038
Within cell	138.72	22	6.31		

Appendix 4.5. - (*continued*)

Duration	757.15	3	252.38	35.95	0.000
Condition x Duration	103.01	3	34.34	4.89	0.004
Within cell	463.34	66	7.02		
Linear by Mask	0.94	1	0.94	0.19	0.668
Condition x Linear x Mask	1.38	1	1.38	0.28	0.604
Within cell	109.74	22	4.99		
Quadratic x Mask	1.76.	1	1.76	0.60	0.445
Condition x Quadratic x Mask	0.38	1	0.38	0.13	0.720
Within cell	64.05	22	2.91		
Cubic x Mask	1.56	1	1.56	0.47	0.502
Condition x Cubic x Mask	5.64	1	5.64	1.68	0.209
Within cell	73.92	22	3.36		
Linear x Duration	72.72	3	24.24	4.43	0.007
Condition x Linear x Duration	6.20	3	2.07	0.38	0.769
Within cell	360.78	66	5.47		
Quadratic x Duration	10.52	3	3.51	0.92	0.436
Condition x Quadratic x Duration	16.69	3	5.56	1.46	0.234
Within cell	251.52	66	3.81		

Appendix 4.5. - (*continued*)

Cubic x Duration	36.66	3	12.22	4.14	0.009
Condition x Cubic x Duration	42.7	3	14.23	4.82	0.004
Within cell	194.72	66	2.95		
Linear x Mask x Duration	7.22	3	2.41	0.89	0.452
Condition x Linear x Mask x Duration	2.70	3	0.90	0.33	0.802
Within cell	178.78	66	2.71		
Quadratic x Mask x Duration	22.75	3	7.58	2.46	0.070
Condition x Quadratic x Mask x Duration	27.54	3	9.18	2.98	0.038
Within cell	203.43	66	3.08		
Cubic x Mask x Duration	11.91	3	3.97	1.20	0.318
Condition x Cubic x Mask x Duration	11.02	3	3.67	1.11	0.353
Within cell	219.04	66	3.32		

Appendix 4.6

Frequency discrimination (Hz) estimates obtained in Experiment 5 using the psychophysical algorithm PEST. A backward masking tone of 1150 Hz was used for all trials.

	Estimate		
	1	2	3
Condition 1			
	139	69	84
	78	98	85
	98	58	95
	56	55	99
	39	38	59
	43	26	#
Condition 2			
	31	24	49
	94	36	51
	35	21	51
	38	39	55
	44	41	59
	26	34	#

Subjects failed to attend the final session.

Appendix 4.7.

Analysis of estimates of frequency discrimination (Hz) from Experiment 5 for tone durations of 50 and 35 ms.

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Between subjects	13847.71	9	1538.63		
Within subjects	8357.29	20	417.86		
Between measures	2499.69	2	1249.84	3.84	0.04
Residual	5857.60	18	325.42		
Total	22205.00	29			

Appendix 4.8.

Comparison of measures of sensory discrimination in Experiment 5 for tone durations and ISIs of 50 (estimates 1 & 2) and 35 ms (estimate 3).

Comparison	difference	SD	't' value	D.F.	significance
Estimates 1 & 2	15.29	10.85	1.41	31	0.169
Estimates 1 & 3	8.54	11.39	0.75	31	0.459
Estimates 2 & 3	23.83	11.39	2.093	31	0.045

Appendix 4.9.

Measures of sensory discrimination from Experiment 6 calculated using the adaptive staircase method and SPSS-X Probit Analysis.

Psychophysical method			
Adaptive method		Probit Analysis	
IT	ATD	IT	ATD
95	-	96	-
106	71	114	103
58	-	54	-
42	100	41	111
49	60	45	74
78	97	126	142
59	128	72	145
74	56	73	60
85	-	97	-
40	53	39	57
86	47	112	51
56	46	57	50
43	57	65	60
61	159	65	194
48	47	54	52

- Subject did not attend the final session.

Appendix 5.6.

The raw scores from Experiment 7 for each block of 24 trials for single and dual-tasks. Each array of 4 figures in the dual-task condition consists of the number of correct responses to both visual and auditory tasks, correct responses to visual but not auditory, correct responses to auditory but not visual, and incorrect responses to both tasks by level of difficulty and condition.

	Sungle-task				Dual-task															
	V(e)	V(d)	A(e)	A(d)	V(easy) A(easy)				V(easy) A(diff)				V(diff) A(easy)				V(diff) A(diff)			
Condition																				
1	24	23	23	19	20	1	0	3	22	2	0	0	24	0	0	0	19	5	0	0
	24	13	11	15	17	5	2	0	16	8	0	0	9	6	3	6	7	4	8	5
	24	23	22	20	22	2	0	0	21	3	0	0	22	1	0	1	20	2	2	0
2	23	22	23	21	20	4	0	0	19	3	2	0	17	1	6	0	12	3	5	4
	24	22	23	21	22	2	0	0	21	2	0	1	24	0	0	0	18	4	1	1
	23	24	18	22	24	0	0	0	21	3	0	0	23	0	1	0	20	2	1	1
3	24	17	21	19	19	5	0	0	16	8	0	0	10	5	6	3	8	3	8	5
	24	23	19	23	24	0	0	0	23	0	1	0	20	2	2	0	23	1	0	0
	23	11	22	13	20	1	0	3	15	9	0	0	17	7	0	0	17	0	1	6
4	24	23	22	18	23	1	0	0	15	9	0	0	24	0	0	0	12	12	0	0
	24	20	16	21	23	1	0	0	21	3	0	0	20	2	2	0	19	1	4	0
	24	23	23	19	23	1	0	0	22	2	0	0	24	0	0	0	19	5	0	0

Appendix 5.7.

Analysis of estimates of IT and ATD from Experiment 7, obtained under two single and dual-task conditions for two levels of difficulty.

Summary Table

Source of Variation	Sums of Squares	*d.f.*	Mean Square	F	Significance
Constant	64389.06	1	64389.06	1307.14	0.000
Within cells	541.85	11	49.26		
Modality	119.17	1	119.17	7.43	0.020
Within cell	176.41	11	16.04		
Task	36.29	2	18.15	2.98	0.072
Within cells	134.04	22	6.09		
Level	171.17	1	171.17	28.35	0.000
Within cells	66.41	11	6.04		
Modality by Task	2.51	2	1.26	0.28	0.761
Within cells	100.15	22	4.55		
Modality by Level	35.01	1	35.01	2.45	0.146
Within cells	157.24	11	14.29		
Task by Level	0.93	2	0.47	0.14	0.868
Within cells	71.74	22	3.26		
Modality by Level by Mask	12.93	2	6.47	1.62	0.222
Within cells	88.07	22	4.00		

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