BIMODAL COMPENSATORY TRACKING AND ATTENTION

by

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ABSTRACT

Subjects performed visual and auditory compensatory tracking separately as well as in dual task combination. In a third condition _Ss_ tracked one signal and copied with his other hand the control movement, thus emitting two identical responses to one input. Normalized mean squared error (NMSE) was lowest in single task, highest in bimodal dual task, with copying/tracking NMSE falling somewhere in between. NMSE was also found to vary as a function of input bandwidth, order of control, and input/plant bandwidth and order of control combinations. The error signal in each loop was sampled once every 100 msec and the samples were then compared. The absolute magnitude of the error in one channel at any given instance was found to be independent of the magnitude of the error in the other loop. This relationship held even when the information processing rate was increased by increasing the input bandwidth.

The results do not support single-channel, information processing theories of attention. Moreover, they indicate a revision of current undifferentiated capacity models of attention (i.e., Kahneman, 1973; Moray, 1967). It was found that the performance of either one of two concurrently performed tracking tasks was a function of the informational content of the other. This result implies that attentional resources are not allocated freely to the various tasks, but

rather, it suggests that the amount of attention allocated to a given task depends and is a weighted function of the concurrent informational content of other, unrelated and distracting,tasks and events. Although, it was fairly evident from the results that subjects could perform continuous tracking tasks simultaneously the observed task interference effects do indicate that the human controller of two, otherwise parallel, multiple single-loop systems does not behave either as a true parallel, or as a serial, information processor.

It is suggested that one of the key functions of man's attentional process is the modulation of stimulus information to enable more or less optimal input to more or less permanent structures in the brain. Thus it is argued, a general undifferentiated capacity theory of attention may not be incompatible with current multiprocessor theories of attention, (Allport, Antonis and Reynolds, 1972). Moreover, in view of supportive existing evidence, it is also suggested that one other functional role played by attention is to enable the establishment in memory of an internal representation of task invariant descriptions than can actively be drawn upon (resources) and implemented to reduce the magnitude of task-related information. Hence, the amount of information, or uncertainty, associated with the performance of a given task is conceived to be the magnitude of discrepancy, or <u>mismatch</u>, between expected and actual task dependent events.

Within such an undifferentiated capacity framework, it is possible, therefore, to account for time-sharing decrements of performance arising directly from either (1) changes in processing linearity, or (2) response delay, or both of these factors without having to appeal to discrete, serial, human information processing models of attention.

We see that the mind is at every stage a theatre of possibilities. Selective consciousness consists in the comparison of these.... the selection of some and the suppression of the rest.

William James

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(The pun in page 23, line 22, playing on the nature-nurture issue is dedicated, with affection, to Dr. Philip T. Smith).

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CHAPTER 1.

INTRODUCTION

Considering the great number of recent studies of attention, it is remarkable how little experimental investigation has required subjects to attend to continuous signals presented simultaneously to more than one sensory modality (Allport, Antonis & Reynolds, 1972; Broadbent, 1956; Cliff, 1972; Kalsbeek , 1967; Wickens, 1976). This is perhaps more striking when we consider that attention is such a central, multisensorial, all pervasive aspect of our conscious experience. Yet the main bulk of research on attention has largely concerned focusing or dividing attention between concurrent stimuli presented to one sensory modality.

Despite the fact that most theories and models of attention were derived from evidence obtained in the context of unimodal stimulus variation, at the theoretical level, attention is generally discussed as an amodal stimulus analyzing process. One has merely to look at current information processing flow-chart models of the human to see the selection stages fed by inputs from various sensory modalities. Thus the assumption is made that such models generalize in descriptive and predictive power to the performance of continuous tasks involving inputs to more than one sensory modality simultaneously, or that require different types of response (Broadbent, 1956a,1958; Mowbray, 1952).

Recent studies reveal, however, that this assumption may no longer be warranted, either with respect to perceptual stages of analysis (Parkinson, 1972; Treisman & Davies, 1972; Schwartz, 1976), or with respect to the response selection and execution stages (McLeod, 1977, 1978).

Treisman and Davies (1972), for example, showed that the amount of interference between concurrently performed signal monitoring tasks could be reduced by presenting the signals to the visual and the auditory modalities instead of only to one of these. Schwartz (1976) also found that reaction-time (RT) to a probe stimulus depended on whether a task performed concurrently involved stimulus presentation to the same or to a different modality. At the response end of the system,McLeod (1977, 1978) has shown that the amount of interference between concurrently performed tasks involving two manual responses could be greatly reduced if the response modality of one of these was changed.

Since, ultimately, a general theory of human attention and performance must incorporate the processing of continuous information presented to more than one sensory modality at once, it behooves us to investigate attention related effects in time-sharing performance in the light of evidence obtained by means of stimulus or task variation between, or among, modalities. This approach appears more promising in the long run, given the patently amodal nature of attention, than one in which discussion of the concept must be restricted to unimodal information processing involving one particular type of response. As it is, only one predictive model of time-shared continuous information processing performance is currently available (Levison, Elkind & Ward, 1971), and even this model was derived from experiments involving presentation of concurrent signals to only one modality.

1.1. - The Division of Attention: A General Statement of the Problem.

The division of attention between two information processing tasks often results in an impairment of performance. That is, either one or both tasks are performed less effectively in conjunction than separately. Although, at first blush, this effect seems intuitively obvious, because people can exert only a limited amount of physical or mental effort at any one moment, the implications of finding, or not finding, such an effect are crucial to our understanding and formulation of man's attentional process. By examining the conditions under which certain kinds of tasks may, or may not, be carried out concurrently without interference we also derive information about what attention is, and is not. One major problem,however,is that it does not suffice simply to know that the performance of two or more simultaneous tasks leads to a decrement in performance relative to carrying out only one. Such an effect may,or may not,be directly attributable to a limitation in attention. Early research on attention in which subjects had to monitor, memorize, or shadow two or more verbal messages (Broadbent, 1958, 1971) clearly demonstrates this. Because of complex memory and response requirements associated with verbal information processing activity, the observed limitations in processing could be interpreted ambiguously both in terms of general limitations in the storage and retrieval of information, or in terms of limitations in the selection of input information. It is necessary, therefore, to specify the effects of time-sharing performance as clearly and precisely as possible, so that factors unrelated to attention may be distinguished. Research on attention involving highly practised subjects, and studies of stimulus-response compatibility also attest to this need (Alluisi,1965; Crossman,1959; Moray & Jordan,1966; Underwood & Moray,1971).

A related problem that accompanies the division of attention between concurrent tasks, concerns the sensitivity of the various performance measures in detecting subtle changes in performance that may relate directly to attention. Gopher and Wickens (1976) note, for instance, that an increase in overall tracking error associated with time-shared tracking may be shown to arise either from an increase in response variability, or to increases in processing delay. Moreover, such an increase in overall tracking error would occur if the subject switched attention between the tasks performing each one at a time. Subtle changes in performance associated with such an attentional switching strategy would not be revealed by overall averages of tracking performance. Hence, even if an increase in overall tracking error is found to accompany time-shared tracking, such an effect tells us very little about the factors underlying the increase. Although, considerably more information concerning the effects of time-sharing on continuous compensatory tracking can be obtained by feedback control theory analysis in the frequency domain (Wickens, 1976), to the extent that the resulting parameters also represent overall averages of tracking behaviour, the various measures tell us little about the dynamics of attentional control on a moment by moment basis. Thus, it is once more insufficient to know that a substantial increase in response variability, or tracking remnant, accompanies time-shared tracking performance. Rather, one must be able to ascertain whether such an increase in tracking remnant arises from a general increase in perceptual-motor noise associated with the division of attention in parallel (Levison, Elkind, & Ward, 1971), or from quite legitimate,non-linear,strategies such as the serial switching of attention from one task to another.

The issue of whether subjects can perform two or more information processing tasks simultaneously,or whether attention may not so be divided but can only be allocated to one task at a time,cannot be resolved if our measures of time-shared performance do not enable us to distinguish between these two alternatives.

The research reported here constitutes an attempt at determining whether subjects can perform two continuous compensatory tracking tasks simultaneously, or whether in carrying out the tasks they behave as serial information processors;carrying out only one task at a time. In order to determine which of these two processing alternatives best characterizes time-shared tracking activity, the magnitude of tracking error in one task was compared with the magnitude of tracking error in the other task performed concurrently, on a moment by moment basis. One of the implications of a single-input information processing model of attention is that if the subject is paying attention to one input he is not simultaneously attending to another. In the context of simultaneous compensatory tracking tasks, such a model implies that if the subject tracks one signal,he may not simultaneously track another,but must switch attention serially from one task to the other. Since the subject's task in compensatory tracking is to maintain the magnitude of perceived tracking error at a minimum, diverting attention from one task to another would produce an increase in tracking error in the 'unattended' task, and a decrease in tracking error in the task receiving attention. Such an inverse relationship in tracking error between the tasks would be characterized statistically as a nonzero negative correlation. Whereas,if the subject could perform both tasks simultaneously without having to trade off performance between the tasks, the magnitude of tracking error in one task would be quite independent of the magnitude of tracking error in the other task.

Since the issue of whether attention can or cannot be divided between simultaneous information processing streams underlies much of the disagreement in the literature, it is important to consider briefly the background research on attention and some of the major theoretical issues to which it has given rise.

1.2. - The Study of Attention: Historical Notes.

At any one moment there is always more information available to our senses than we can possibly attend to. To the extent that this is true,the human being is by nature a selective, limited capacity, information processor. Whether this limitation in processing also implies that each of the sources must be dealt with selectively, in turn,is an old issue in Psychology. The formal study of this selectivity and general limitation in processing information is the study of attention.

Questions concerning whether people are able to divide their attention between concurrent objects or events can be traced back to Plato and Aristotle. Perhaps the earliest objective study of a person's ability to attend to two signals occurring simultaneously was the investigation of the 'personal equation' problem that puzzled both astronomers and psychologists at the end of the eighteenth century (Bessel, 1823; Russell, Dugan & Stewart, 1945), and still does (Sternberg & Knoll, 1972). Investigation of the problem revealed that two signals presented in synchrony to the visual and auditory modalities could not be attended to simultaneously. The results of von Tchisch's (1885) famous complication clock experiments, and the object counting experiments by Hamilton (1859), indicated that cognitive processing of information from various sources may not be able to proceed simultaneously; or that if it does, it is at a distinct cost in performance.

The first proponent of attention as a serial information processing activity was probably Hylan (1903). He argued, offering supporting evidence, that attention is limited in capacity, not because of a spreading of attention over the objects surveyed as Hamilton (1859) had suggested, but because of an all-or-none fluctuation, or switching of attention from one element to another.

Theoretical treatment of the problem by William James (1890), Mach (1885) and early experimentation by Jastrow (1891), Hamilton (1859) and others in this period did much to establish attention as a central concept in the study of mental life (Ach, 1905; Dallenbach, 1913; Geissler, 1907; Titchener, 1908; Watt, 1904). Titchener (1908) for example dedicated much detail in his famous lectures to the various aspects of attention, and also in that same year ,Pillsbury published his book on attention. But soon after, disagreement concerning both measurement and definition of attention, coupled with the rise in popularity of Behaviorism (Watson, 1913),an approach which categorically excluded all unobservable behavioral processes from psychological study, led to a long period of selective neglect of the problem.

Fortunately, the attentional demands placed on human operators by the host of evermore complex devices that emerged to meet the emergencies of warfare during World War II, soon brought home to psychologists and engineers alike, the crucial role of attention in human performance. Important developments in communication and information theory, as well as the various contributions to human attention and performance theory by such men as Craik (1948), Hick (1952), Broadbent (1952a, b), Cherry (1953) and others, paved the way for the development of an information-communication theory of human performance (Broadbent, 1958). Since then, theoretical and experimental studies of attention have proliferated.

1.3. - Theoretical Issues.

Single-Input Limited Capacity Theories.

Some theories of attention explain the difficulty in dividing attention between concurrent tasks on the assumption that simultaneous sources of information can only be analyzed serially by a unitary attentional information processing system of limited capacity. When two or more signals that convey information to the subject are presented in synchrony, the sensory inputs corresponding to the signals compete for a central, information processing channel of limited capacity that can deal with only one signal at a time. Broadbent (1958) proposed such a single-input attentional model in the context of split-span dichotic listening experiments. Estes and Taylor (1967, 1966) proposed a model of this type for visual information processing. Franzen, Markowitz and Swets (1970) also proposed this model for the processing of near-threshold vibrotactile information. Moray (1970 a,b) proposed such a model for dichotic tone discrimination.

Broadbent (1958) proposed the first complete, empirically testable theory of attention. Essentially an interpretation of the observed limitation in human ability to deal with several sources of stimulation occurring simultaneously or in quick succession (Cherry, 1953; Craik, 1948; Welford, 1952), Broadbent's theory was based on an analogy between human perceptual, and communication systems. The limitations in the ability to attend to several simultaneous sources of information at once, were thought to parallel in certain ways those of an information processing channel of limited capacity (Shannon, 1948).

According to the model, sensory inputs from distinct sources, or channels, would be individually analyzed and placed in a short-term sensory store, or memory buffer, whose function was to hold sensory input information until it could be processed further. Up to this stage of analysis of information into the sensory buffer, Broadbent's model represents a parallel preattentional information processing system. Thus, to the extent that information could arrive from distinct sources, such as from two different speakers at a cocktail party, there would seem to be no apparent limit to the amount of information that could be processed in parallel into the store. Beyond the sensory buffer, however, Broadbent suggested that a drastic transition from parallel to serial analysis took place. This reduction in processing ability was thought to represent the transition from multiple sensory registration to unitary, conscious, attentional analysis. Therefore, between the memory buffer and the single-input attentional information processing channel, Broadbent placed a switch whose function was to enable the selection of any one particular input channel from the buffer. Once selected, the phenomenal experience was that of attending to a particular message or signal. Thus,even though early preattentive attentional processing may make available information from different inputs simultaneously in the memory buffer, we can attend to only one input at a time. Yet information from two or more inputs could be processed quite flexibly,without a loss of information,provided the time taken to shift and set the filter from one input to another in the buffer did not exceed the maximum storage-time characteristics of the buffer. Accordingly, it is possible to deal with two simultaneous stimuli, but only if the analysis of one is completed before the other is lost from the short-term store.

An important implication of such single-input limited capacity theories of attention is that the time taken to process concurrent signals that convey information to the subject would always take longer than to process only one. This is because the processing of only one signal would be postponed occasionally to accommodate processing another signal. The limitations in processing simultaneous events are thought, therefore, to depend on exceeding the rate at which information can be transmitted through the channel. Hence, single-input information processing theories of attention assume a general limitation on perception.

Numerous studies have shown that when subjects must deal with two simultaneous signals they may often respond to only one (e.g. Colavita, 1971; Moray & O'Brien, 1967; Moray, 1970 a,b; Mowbray, 1954; Treisman & Geffen, 1968). In Mowbray's (1954) study, for example, subjects were presented with a visual and an auditory message simultaneously which were to be used in a complex task. The subjects were unable to use the simultaneity of the messages not perceiving them as such. In a simulation of the air-traffic controller's task, Webster and Thompson (1954) also noted that the subjects could not make proper use of simultaneous auditory messages, except when these were highly redundant.

Perhaps the best demonstration of single-input limited information processing activity is provided by the experiments of Axelrod and his colleagues (Axelrod, Guzy & Diamond, 1968; Axelrod

& Guzy, 1968; Axelrod & Nakao, 1974; Guzy & Axelrod, 1972). These researchers reasoned that if subjects must divide their attention between two locations in order to respond discriminatively to certain stimuli, the subjects would be more likely to miss perceiving and responding to some stimuli, relative to a condition in which the stimuli could come from only one location. Axelrod and Diamond (1968), used a method of constant stimuli to determine subjects' perceived rate of auditory click presentations as a function of presentation to one ear, or dichotically to both ears. They found that as the rate of click presentation was increased the perceived rate was deemed slower in the dichotic presentation condition than the equivalent rate of click presentation to only one ear. Guzy and Axelrod (1972) went on to show that estimates of the number of clicks occurring on each trial were found to decrease as a function of the rate of alternate dichotic click presentation, relative to a monotic presentation condition. Lastly, Axelrod and Nakao (1974) have shown that these effects are central, and not specific to the auditory modality. They showed that these results could be obtained when stimulation involved repeated to one hand, or alternate tapping of the two hands.

Broadbent (1958) suggested that the transition from parallel to serial processing, or many- to-one convergence processing 'bottleneck', occurred at the level of input selection.

As a result,most experimental testing of the theory was concerned with input selection aspects of attention. Welford (1959) criticized the location of the processing bottleneck and suggested extending the 'length' of the limited capacity serial information processing channel to encompass the response selection and response execution stages as well. Crossman (1956) and Leonard (1959) had already shown that the delay in processing a signal depends on input output response compatibility (see also Keele, 1973; Smith, 1976) and may also be shown to depend,for a given fixed set of input signals,on whether a single or several responses are required (Donders, 1868; Brebner & Gordon, 1962, 1964; Welford, 1968). Welford attributed the added delay in responding to more than one signal presented simultaneously,or in close succession,to a limited-capacity central translation mechanism whose function was to convert perception into action,and that could only deal with one signal at a time. Welford drew from evidence given by Craik (1948) involving a pursuit tracking task. The pursuit tracking tasks he examined required moving a lever, or turning a steering wheel, in order to keep a pointer in line with a target which moved irregularly from side to side. Craik had noticed that the signal trace generated by the pointer did not follow the target smoothly, but showed a series of oscillations. Closer examination revealed that the subject's corrections of misalignment between the pointer and the target were not continuous, but were made at discrete intervals of about 500 msec. Craik had reasoned that if a signal had to be processed along a chain of synapses to activate a response, there would be no reason why a continuous signal should not lead to a continuous response, even if lagging a little bit behind the input. In accounting for such an effect,Craik suggested a logical interpretation. The presentation of information from one source would immediately initiate the computation of a finite amount of information from it. During the processing of this information, further input which might disturb it was blocked. The outcome of this would be that both the acquisition of data and the initiation of responses to it would be intermittent, reflecting the discrete nature of the underlying signal processing operations.

Welford suggested that when the subject was required to process more than one signal at a time,the difficulty arose because responses to the various inputs could only be organized serially. That is, a response to a signal not occupying the information processing channel would not be emitted until the channel was fully cleared from processing the signal occupying it.

Recently,Cliff (1971) formulated and tested a model of time-shared tracking performance based on Welford's strict single channel-theory. Cliff showed that the tracking behavior of a subject engaged in continuous compensatory tracking of a visual stimulus and auditory shadowing of a verbal message, could be simulated quite well by increasing the processing delay parameter in the model. He assumed that if the subject could process only one task at a time,he would switch from one task to the other. The result of switching attention away from the tracking task was assumed to produce an added delay in the detection and subsequent correction of tracking error.

Welford's single channel theory is formally very similar to Broadbent's filter theory, except for the location of the processing 'bottleneck'. In both theories,the effects of divided attention are to produce a decrease in performance that may be attributed to an increase in processing delay or to a loss of information when the capacity of the single channel is exceeded. The association between divided attention and an increase in processing time has been particularly noticeable in reaction time studies of attention (e.g. Briggs, Peters & Fisher, 1972; Keele, 1967; Kristofferson,1967; La Berge,1973 ; Posner & Boies, 1971). Although some researchers have also found delays in processing to accompany time-shared tracking behavior (Jex, 1967; Watson, 1972) the effect has not been consistently found. For example, Allan, Clement and Jex (1970), Baty (1972) Levison (1966), Levison, Elkind and Ward (1971) and Wickens (1976) found no such delay in processing. But in all these studies, however,a considerable reduction in the fidelity of the information transmitted,as indicated by an increase in variability or noise in subject's response,was found. Specifically, the effect of overloading the limited capacity channel in a continuous compensatory tracking task would be to produce a progressive increase in the lag between the tracking input and subject's output. When this lag becomes too great,the subject must reset the lag to a minimum value, at a distinct cost both in terms of information transmitted, and in terms of an injection of responses not necessarily related to the input. The outcome of such tracking intermittency would be to add to an overall measure of input-output tracking lag, and a loss in tracking linearity. Overloading of a single input attentional system could therefore occur within a single tracking task by increasing the rate of input information, or by the requirement to time share tracking with one or more additional tasks.

Analyzer Theory

Treisman (1969) also questioned the emphasis placed by filter theory on the rate of incoming information as such (Fairbanks, Guttman & Miron, 1957; Moray & Taylor, 1958; Treisman, 1965a). Treisman (1960, 1964),pointing out that not all unattended information was gated out (Cherry, 1953; Moray, 1959),argued for a modification of the all-or-none nature of the filter. Treisman suggested that the selection process, or filter, rather than reducing, or blocking out, the amount of information available in the unattended channels, was selective in the sense that such information was not analyzed to the same extent as that in attended channels. Accordingly, attended information would be analyzed to a higher or deeper level than unattended information. To the extent that only a few features of a highly meaningful or overlearned stimulus may be all that is necessary for its identification, such material occurring on an unattended channel may actually be processed to a level where it may be recognized. That is, a subject attending to one source of information may actually identify his or her own name, or a word, or event that is highly predictable from preceding context, but may not recognize or make sense of any other words or events occurring in an otherwise unattended message. Although Treisman used the concept of attenuation to describe the operation of the filter on the unattended channels, she did not imply that the actual information conveyed by a channel or signal was altered in any way. Rather, the difference in level to which information was allowed to be processed was the determinant of whether a source was attended or not. This is an important principle because it implies that attention may be graded so that full analysis of only one source may be possible at one extreme, and partial low level analysis of many sources at the other. The filter concept therefore is modified so that rather than all-or-none, in Treisman's theory it becomes probabilistic. There is a greater probability of words being recognized in an attended message than words in an unattended message,since in comparison,a greater number of words in the attended, selected, message are processed to a level enabling recognition.

Selection in Treisman's theory was conceived as a hierarchical process, the elements of which were individual perceptual analyzers (Sutherland, 1959). Analysis of incoming information was serial within each analyzer, as Sutherland had shown, but processing of various inputs could proceed in parallel between various systems. Although it is not easy to tease out from the various levels of analysis in Treisman's model just what constitutes an analyzer or not, for our purposes it serves to note, that presentation to two,or more distinct sensory modalities of modality specific stimuli, guarantees processing independence ; at least with respect to early perceptual analysis (Treisman & Davies, 1972). Hence,the limitations of attention are assumed to arise from exceeding the capacity of individual analyzers, and not of a serial scanning filter.

Parallel Processing Models

In partial contrast to the single-input, limited capacity, serial processing models of attention, other theories maintain that simultaneous processing of distinct sensory information channels is generally possible, but,with an upper limit on the unattended message, since in comparison, a greater number of words in the attended, selected, message are processed to a level enabling recognition.

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Parallel Processing Models

In partial contrast to the single-input, limited capacity, serial processing models of attention, other theories maintain that simultaneous processing of distinct sensory information channels is generally possible, but, with an upper limit on the total amount of information that can be processed at any one time. Thus,a multiple-input information processing channel is implied. Researchers vary in their views, however, with respect to whether parallel processing of concurrent signals imposes demands on a limited-capacity information processing channel. For example, Posner and Keele (1970) have argued that certain tasks may be carried out in parallel without interference, while other tasks may not, depending on whether the various information processing operations inherent to each task require simultaneous access to a single-input limited capacity information processing mechanism,or not. Interference between tasks performed concurrently is thought to arise,therefore, from certain task-specific operations which may not be performed simultaneously.

Other researchers have suggested more flexible attentional systems to account for the difficulty in divided attention. These theorists assume that total processing capacity is limited as well, and that some input is simultaneously processed from many channels. Attention is assumed to control the relative amount of information processed in particular channels. Moray (1967, 1969), Treisman (1969), and Neisser (1967) have advanced models of this type in the context of evidence obtained primarily from dichotic listening and speech shadowing experiments. Rumelhart (1970), and Norman and Rumelhart (1970) have also proposed a model like this from studies of visual information processing. Neisser (1967) noted the need to incorporate in these types of models a 'preattentive' system whose function would be to direct attention to the relevant channels. Recently, Kahneman (1973) has also acknowledged this need, and in a model very similar to that suggested by Moray (1967) incorporated such a process. He aptly termed this process the 'allocation policy'. These models imply non-specific interference between tasks, but they do postulate that interference between tasks will take place depending on their cumulative processing capacity requirements. Both serial and parallel processing of concurrent inputs is also implied in these models. Treisman (1969) assumed serial analysis within each input analyzer, and parallel processing between analyzers. Kahneman (1973) and Moray (1967) assume multiple-channel and single-channel processing to suit processing capacity limitations.

Other researchers argue, however, that the decrement in performance that accompanies multitask conditions relative to single task performance, has little to do with the detection, perception, and recognition of task related information; features commonly associated with the act of attending to objects and events. These models do not imply that the limitations in processing simultaneous inputs arises from a general limitation in parallel processing of sensory information. Rather, they suggest all sensory information is already identified and recognized by the time a decision is made concerning whether to process it further for permanent storage in memory, or to respond to it. These theories assume no limitations in processing capacity during recognition, and minimal interchannel interference during the analysis of concurrent inputs. The emphasis is placed, however, on short-term memory capacity limitations following recognition, at the stages of information storage in permanent memory (Atkinson & Shiffrin, 1968), and at the response selection and execution stages of analysis (Deutsch & Deutsch, 1963; Keele, 1973; Norman, 1968; Posner & Boies, 1971; Welford, 1959). Deutsch and Deutsch (1963), and Deutsch, Deutsch and Lindsay (1967) have proposed such a model for auditory processing of information. Hochberg (1970) also proposed a more general model with similar properties. Shiffrin and Gardner (1972), Shiffrin, Craig and Cohen (1973), and Schiffrin and Schneider (1977) have proposed such a model for visual processing and general sensory processing. LaBerge (1973) has also argued for a model of this type based on reaction-time data as have Posner and Warren (1972), and Posner and Snyder (1975).

Undifferentiated Capacity Theories

Moray (1967) drew a careful analogy between the brain as organic processor of information and a digital computer. According to this account man may be conceived to possess, somewhere in his brain, a bank of general-purpose processors, flexibly operating as processors one moment, and as stores the next. These units in conjunction with permanent processing structures would enable far greater versatility than that implicit in filter theory. For example it would be able to accommodate for improvements in performance due to practice several orders of magnitude greater than could be expected from a filter model (Allport, Antonis & Reynolds, 1972; Davis, Moray & Treisman, 1961; Moray & Jordan, 1966; Mowbray & Rhoades, 1959). Moray suggested that these general-purpose processing units would be allocated to meet the various processing requirements set by the nature of the tasks themselves. That is the observed limitation in the concurrent performance of distinct information processing tasks is thought to arise when there are fewer processing units, or resources, available than the total number required by the tasks. The 'bottleneck' therefore does not depend on the rate of incoming information *per se*, but on the total number of available processing units, or processing *space*. In effect, Moray suggested we consider the human operator as a "limited capacity *central processor* whose organization can be flexibly altered by internal self-programming" (Moray, 1967, p. 85 his italics). Thus viewed, attention becomes a more or less optimal skill, whereby the human, in interaction with his environment and his experience of it, is able to transform and make decisions on information available to his senses (Moray, 1977).

Recently, Kahneman (1973) has developed and extended Moray's ideas, suggesting a capacity model that views man as possessing somewhere in his brain a 'pool' of processing resources, or effort, which may be allocated to the various functions performed. The amount of effort invested on a particular task, or allocation policy, would be influenced directly by internal and external factors, such as arousal, or by various selection rules.

The undifferentiated capacity theory of attention assumes, therefore, that the difficulty in attending to several concurrent sources of stimulation arises as a function of the difference between the capacity required to do so, and the processing capacity actually available. Interference between tasks is nonspecific in the sense that it does not depend on the transformations, or operations, specific to a particular set of tasks, but on the total available processing capacity, or effort. Therefore, parallel processing of information emanating from various sources at once is possible, but always at a distinct cost in processing capacity. This is a distinguishing feature from a model such as that of Posner & Keele (1970) discussed earlier which postulates that processing capacity is not always required by all tasks. It is possible to show, therefore, in accordance with the undifferentiated capacity theory, that three different tasks may be carried out concurrently two at a time, in any combination, without apparent interference,but might not be performed all at once without a general,or a specific,decrement of performance. That is, a pair of tasks may still be carried out without interference, at the expense of a third, or all tasks will suffer from mutual interference. This would be true even if it could be shown that the three tasks performed individually did not require access to the single channel. Posner & Keele's (1970) model would predict no interference between the tasks if performed all at once. Multitask interference would only be predicted if the further assumption was made that at least two of the tasks now competed for access to the channel. This would have to be the case, because their model accommodates simultaneous processing between tasks that require no attention ,and at least one that does.

The undifferentiated capacity theory, however, implies that only when concurrently performed tasks are all extremely difficult and demanding, should strict single-channel switching of attention be observed. Such a performance optimizing strategy would be invoked, when the capacity limitation is so severe that shunting attention between the tasks enables some adequate execution of all tasks, albeit with difficulty, instead of relative success in some and calamitous failure in others (Kahneman, 1973). An excellent example of such task performance co-ordination is given by Kalsbeek (1964). Kalsbeek found that subjects could perform in time, but only after considerable practice, the double task of responding with either foot to two tones of different pitch along with the manual sorting of rods of different length. As the subjects became more skilled, he noted that the subjects tended to build up a rythmic pattern of performance in which the two tasks were regularly interdigitated. When this optimal rate of responding was achieved, the impairment of performance produced by combining the two tasks was greatly reduced. It is as if subjects had learned to integrate the two tasks into a more complex task. The discrete tracking studies conducted by Pew (1966), lend support to the notion that attention serves to optimize the flow of information through more efficient encoding and decoding of task related information. Attention, therefore, relates to the deployment of processing capacity in a manner which becomes more efficient and effective with experience. Thus, the undifferentiated capacity model implies that the improvement in task performance that accompanies experience with the particular task, does not arise from any increase in the total number of processing resources, but from the efficiency with which they are used. Kalsbeek's experiment implies, that the various components of a task may be interdigitated with components from another, to the point that performance appears to be simultaneous for the two tasks. The rapid coordination of information from the two tasks may indeed reduce the apparent difficulty of the tasks, but it is unlikely that processing efficiency leads to the bypassing of the limited capacity processor; either with respect to the translation mechanism, or the perceptual selection process. It is sometimes suggested that the central processing channel can deal with two sets of data, or two distinct channels of information, simultaneously. More likely, however, seeming automaticity rather than the bypassing of central processing mechanisms is the underlying factor. This is indicated in an experiment by Leonard (1953) that involved a comparison of subjects' performance in two serial-reaction tasks. In one of the tasks presentation of a signal was triggered by completion of the response to the previous signal. In the other task, each signal was indicated before the subject had initiated the response to the previous signal. Overall, subjects were faster in responding to the second task, and reported having the uncanny feeling of being removed from the task, as if they were spectators to their own actions, the actions themselves proceeding without conscious control. Since the signals were visual, and the responses so simple, Leonard suggested the subjects were able, in time, to reduce to a minimum the monitoring of essentially kinesthetic feed-back (See also Annet, 1966; Davis, 1956; Marrill, 1957). It would appear that practice serves to increase the accuracy of simple actions, to the point that they do not need to be checked, for in a sense the feedback becomes redundant. Whenever the monitoring of certain feedback signals may be dispensed with because they no longer provide relevant information we should expect feelings of automaticity and unconscious control. This does not mean, however, that the tasks no longer require processing capacity, it just means that the subject has learned with practice to reduce uncertainty about responding, thus reducing the amount of feedback information inherent in the task(s). The result would be a reduction in the amount of information conveyed by the task. This point relates directly to a notion of channel capacity, and illustrates some existing confusion in the literature concerning the meaning of the concept. Some researchers have understood the concept of information channel capacity to refer to the actual rate of information transmitted (in bits/sec.) in a given set of circumstances. But this use of the concept of channel capacity, though appropriate in some cases, departs from its formal definition in information theory (Shannon, 1948) where it refers to a transmission rate optimized by optimal coding. Therefore, with respect to the human, most notable as an adaptive information processing system (Young, 1969), the amount of information that need be processed from any one task would vary as a function of his or her ability to optimize the coding of input information. Miller (1956), for example, showed that a subject skilled in recoding could process three times as much information as he could before training. Indeed, a skilled pianist may be able to play up to 25 notes per second while sight reading music from a score (Hughes, 1915).

Structural vs. Capacity Interference

Kahneman (1973) draws a further distinction between interference arising from limitations in processing capacity, and interference arising from tasks which by their very nature use common input or output processing structures. There are numerous instances in the literature which clearly indicate interference due to capacity limitations (e.g. Johnston, Greenberg, Fisher & Martin, 1970; Trumbo, Noble & Swink, 1967; Kahneman & Peavler, 1969; Baddeley, Scott, Drynan & Smith, 1969; Murdock, 1965). Whereas in other instances, the degree of interference between concurrently performed tasks is by far greater than that which would be expected as arising from capacity limitations alone (Baddeley, Grant, Wight & Thomson, 1975; Brooks, 1967, 1968, 1970; Greenwald, 1970a,c). Treisman and Davies (1972) for example, showed a reduction in the degree of interference between monitoring tasks could be obtained if the signals monitored were presented to different modalities, or analyzers, instead of only to one. Some researchers have argued that in effect all interference between tasks performed concurrently, arises from competition among the tasks for special purpose processors (Allport, Antonis & Reynolds, 1972; Brooks, 1967; Marcel, 1970). The performance of concurrent information processing tasks involving the same modality, representational system, or response system, will suffer from structural interference and not simply from shortages in processing capacity.

There is at present little evidence that unambiguously differentiates capacity from structural interference. As Broadbent (1971) points out, it is perhaps the level of difficulty of the tasks which is a critical factor determining whether a decrement of performance will accompany a requirement to time-share between them. Broadbent (1958), for instance, reported experiments in which subjects were impaired on a manual tracking task when carrying out a simultaneous speech monitoring task. The amount of interference was found to vary as a function of the difficulty of the listening task. Certainly, as Peterson (1969) demonstrated, all multitask interference cannot be due to rivalry for special purpose processing systems. He showed that subjects could carry out complex covert problem solving activity, including the solution of anagrams, while at the same time engaging in rapid counting of numbers, or in rapid recitation of the alphabet. Presumably the considerable processing demands placed on the verbal analyzing system did not produce the structural interference predicted by a differentiated capacity theory of attention such as that implicit in Allport et al (1972). In this context, the familiar children's game of tapping the head regularly with one hand while simultaneously rubbing in circular motions, the tummy with the other, provides an excellent example of structural interference, or motor crosstalk. With practice, however, the difficulty in carrying out the tasks simultaneously is greatly reduced, even to the extent that seeming automaticity is reached. If the additional requirement to speed up the tapping but slow down the rubbing is introduced however, we notice at once an increase in difficulty. The point is made all the more revealing when the tasks are reversed, so that the hand doing the tapping now does the rubbing, and vice versa.

CHAPTER 2.

INTRODUCTION TO THE RESEARCH

It is not sufficient simply to show that a decrement in task performance accompanies the requirement to time-share attention between concurrently performed tasks, to infer conclusively single-input, serial, information processing theories of attention. Nor is it sufficient in order to disprove such theories to show that highly trained subjects may, in time, carry out complex information processing tasks concurrently with little or no interference. Kalsbeek's (1964) study, cited earlier, clearly demonstrates this. Serial alternation between the tasks is a possibility that remains until it is shown that the performance of one task does not simultaneously preclude the performance of another, on a moment to moment basis. Indeed, much of the disagreement in the literature of attention stems directly from the fact that a time-sharing decrement in performance associated with the requirement to divide attention between concurrent information processing tasks, may be explained both in terms of serial (Broadbent, 1958; 1971; Welford, 1959) and parallel, multiple-channel, limited capacity information processing theories (Kahneman, 1973; Levison, Elkind & Ward, 1971; Moray, 1967). A theoretical problem directly associated with this issue is that, as Lindsay (1970) has already pointed out, single-channel limited capacity theories of attention receive support by default whenever a time-sharing decrement in task performance is observed. Yet,as the experiments by Treisman and Davies (1973), and by McLeod (1977, 1978) clearly indicate, factors other than the requirement to divide attention per se may underlie such a time-sharing decrement in task performance. Effects other than those related directly to limitations in attention, may, therefore, be erroneously attributed to serial, single-channel, processing.

The striking feature differentiating serial from parallel, limited capacity, information processing models of attention, however, is not whether subjects can,or cannot,perform concurrent tasks as efficiently in conjunction as separately. Rather, the crucial difference relates specifically to the manner in which information is processed. Serial information processing models postulate that the capacity of the information processing system is applied to the information channels one at a time, whereas parallel models postulate that attentional capacity, or effort, is deployed simultaneously to the various information channels. Therefore, the issue as to whether attention can ,or cannot, be divided between concurrent information streams must relate specifically to the dynamics of the attentional system on a moment to moment basis. In this sense,the implications of serial and parallel models of attention in the performance of continuous information processing tasks are clearly different. At any one moment serial models assume that only task-related information pertaining to one task can occupy the attentional limited capacity system. Limited capacity, parallel, information processing models, on the other hand, allow for processing of task-related information from more than one concurrent task.

2.1.- On telling serial from parallel information processing in continuous attentional performance: An analogy.

Let us consider a simple analogy that sets a perspective from which to view a not so simple issue. Consider the following task. A man is required to keep a rectangular object from sliding down a frictionless ramp towards him. In order to do so he is provided with a fireman's hose attached to a hydrant issuing water at a constant rate. By aiming the water jet squarely on the object, the man can repel the object up the ramp to a certain level and keep it there. It is easy to note, by placing a mark on the ramp, just how high on the ramp the man can keep the object at bay. Now assume further that we ask the man to perform an additional task. We place another object, identical in every respect to the first, next to it on the ramp and ask the man to do his best to keep both objects as high on the ramp as possible. It is evident that since the man has available only one hose to repel the objects, the only way he can perform the task is by shifting, and aiming, the hose from one object to the other in serial alternating fashion.

Given that the rate at which water is pumped is constant, the man would not be able to keep back both objects as high up on the ramp as he was able to keep only one. Moreover, the crucial point here is that regardless of how rapidly the man could shift the hose between the objects, only one would be receiving the jet of water at a time. Therefore, quite irrespective of the switching rate, if we recorded the covariant behavior of the blocks over time, at any one moment, one would always be moving in a direction opposite from the other. Hence, the direction of displacement of one object would always be inversely related to the other object. Note that the variation in movement of the blocks about their mean position would be tied to the hose switching rate so that at low switching rates the blocks would move considerably more up and down the ramp than at high switching rates where the movement of each block may become imperceptible.

Consider an alternative situation where besides giving the man two objects to propel up the ramp, we provide him with a 'y' spout whereby he can send two jets of water from the same hose. The man can now proceed to aim each jet of water at a corresponding object, and keep both objects more or less stationary on the ramp. We should, of course, realize at once that since the hydrant provides water at a constant rate, the rate at which the water issues from each outlet would be halved. Hence, the man would not be able, in this case either to propel the objects as far back up the ramp as he could only one. In this case, however, the negative correlation observed between the motion of the objects in the single-hose, dual-task,condition would not be present. Note too,that with respect to the two systems implemented in the analogy, the only way to distinguish between the one-jet two-block, and two-jet two-block dual-task conditions, given that we can only use the behavioral observation of the blocks as data, is to examine the covariation between the movement of the blocks. Examination of the average position of the blocks on the ramp for example is not a sufficient prerequisite to infer correctly whether the man is using the 'y' spout or not. Moreover, examination of the variability of movement of the blocks about their respective mean position does not enable a distinction either, if it so happens that the man was able to switch the single-spout hose sufficiently fast so as to minimize the descent of the blocks. But, as we have already noted, in the single water jet,two-block,condition,regardless how small the movement of the blocks, indicating rapid switching, a negative correlation would always be found to characterize the behavior of the blocks. Fortunately, the correlation coefficient between pairs of observations is independent of the magnitude of the elements, indicating only the degree of correspondence between the elements.

Although the introduction of such a simple analogy points directly and precisely at the issue of whether attention can be deployed simultaneously in parallel to concurrent tasks, or must be switched serially between the tasks,certain points should be made clear. There is,of course,no reason to believe that attentional capacity is fixed,as was the water pressure of the hydrant in the analogy,nor that the various channels that can be allocated to the various sources of information,and which draw from a common pool of processing capacity,need share identical characteristics. But,although the analogy represents a decidedly too simple caricature of the problem, it serves to illustrate how, at least in principle,serial and parallel information processing alternative accounts of time-shared attentional performance may be distinguished. If a subject is to perform two continuous information processing tasks simultaneously,serial models predict an inverse relationship in performance between the tasks,whereas, processing independence is predicted by parallel models.

2.2. - The Compensatory Tracking Paradigm.

It is possible to create in the laboratory an experimental situation enabling the distinction between serial and parallel information processing attentional behavior. Assume a condition in which subject's task is to keep a randomly moving visual stimulus, say a spot on a screen, as steadily still as possible. To do so we provide him or her with a manual control which can be moved suitably to reduce the motion of the spot. Hence the subject observes only the magnitude of error, or his inability to predict and cancel the motion of the spot, by appropriate movements of the control. If we ask the subject to perform this task paying full attention to keeping the observed error at a minimum, we have a situation where the subject compensates by appropriate movements of the control for a perceived magnitude of error. Such a feedback control situation is depicted in Figure 2.1. This is a single-loop feedback system (disregarding feedbacks internal to the operator), and represents the simplest manual control system. The system forcing function, or tracking input, i(t), is usually chosen to be a random, or random-appearing, time function which has stationary or quasi-stationary properties. This is because if the tracking input is not random appearing, but repeats over relatively short time intervals, the operator can often detect and anticipate the repetitive, or deterministic, nature of the input and adjusts his response accordingly (Poulton, 1950b). Such a higher-order type of behavior would imply the presence in the system of additional signal paths that would in turn, no longer permit the assumption of a single-loop feedback system. The input to the operator, in compensatory tracking, is a stimulus which shows only the algebraic difference, or tracking error e(t), between the tracking input i(t) and controlled element output, or system output, m(t). Normally,

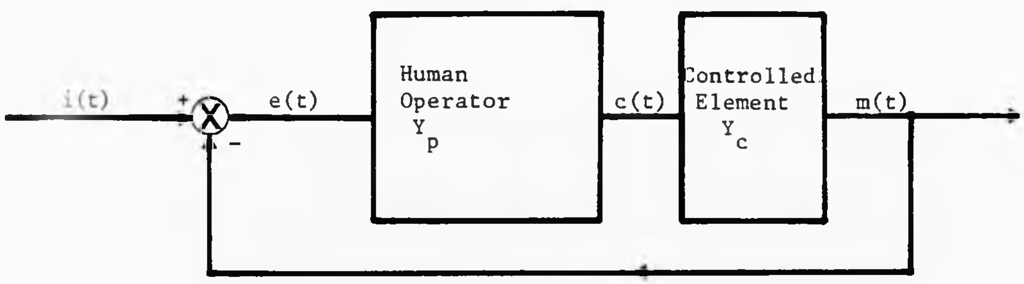

Figure 2.1. - Single-Loop Manual Control System.

$i(t)$ = Tracking Input Signal in the Time Domain

$e(t)$ = Error Signal.

$c(t)$ = Operator Output

$m(t)$ = System Output

Y_p = Human Operator Describing Function

Y_c = Controlled Element Describing Function the operator's task is to reduce the magnitude of displayed error e(t) by trying to keep it on a given stationary reference. The operator can accomplish this by manipulative control action, c(t), which alters the output of the controlled element (i.e., a steering wheel, turn knob, joystick,etc...) and produces the system output m(t), being controlled. Thus by appropriate manipulation of the controlled element, the operator can make the system output,m(t), closely resemble the tracking input,i(t); or in other words, make the output track,or follow,the input. The quality of tracking is given by the magnitude of the error, e(t).

The compensatory tracking paradigm is particularly well suited to the study of attention in continuous information processing tasks.Since,essentially,the subject's task is to reduce the magnitude of perceived error by manipulating a control, the compensatory tracking task represents, therefore, a prototype of continuous, nonverbal, psychomotor information processing activity. Because of the simplicity of the task, a situation can be established in which (1) the parameters of the tracking input can be precisely controlled and reproduced,(2) where the influence of memory and response factors can be minimized,and(3) where powerful analytic techniques can be applied (Licklider, 1960).

2.3 - The Compensatory Tracking Paradigm: Background Research.

Engineers first became interested in the human operator as a dynamic system when power controls, rather than the more simple direct linkage control devices, were given to the operator to control during World War II. Interest in tracking was stimulated, because, the progressive sophistication of manual control devices developed for modern fire control problems necessitated a more detailed, and precise, description of human operator dynamics than had previously been necessary. The increased speed of enemy aircraft meant that pilots and gunners could no longer compute leads in their head, (in the same sense that one aims ahead of a moving object to be sure to hit it) indicating that the characteristics of the human controller could no longer be ignored. By understanding the tracking performance characteristics of the operator, and by tailoring the equipment to his imposed limitations, it became possible to show that naive subjects, provided with optimal controls, were able to out-perform trained gunners, on flexible gunnery simulator tests, when the trained gunners used existing equipment.

It was Tustin (1944, 1947) along with other researchers in this period (James, Nichols and Phillips, 1947; Weiss, 1943, 1945) who pioneered the application of the well developed theory of 'Linear Servo-Mechanisms' to the human operator involved in tracking. Tustin examined the nature of the relationship between the operator's perceived error,and his subsequent manual response to it,in the hope that it would be found to be approximately linear, thus enabling an analysis of the human operator's behavior as that of a linear servo-mechanism; a technique that had proven most effective when applied to the problem of automatic following. The results of his compensatory tracking experiments revealed that although the operator could behave for low tracking input frequencies,in remarkably linear fashion,(disregarding the operator's inherent effective processing delay.When tracking a first order system as much as 90-95% of an operator's response may be linearly correlated with the input), as much as 50% of his tracking error could be shown to arise from nonlinearities in the operator's response not directly ascribable to a linear transformation on the input. Tustin termed this random variability in the operator's response the <u>remnant</u>,or component of the operator output unrelated to the input. Tustin suggested that this variability in the operator's response could be conceived as white noise injected at the operator's output, presumably at the stages of response organization and execution. Although, in later years the origin of output remnant has been both thought to occur at input or at output stages, one interpretation of the remnant is that of a perturbing noise process added to the operator's information processing channel, in a similar sense to the way that neural noise is hypothesized to perturb signal processing in the classical signal detection paradigm (Green & Swets, 1966). For a detailed analysis of human controller remnant see Levison, Kleinman and Baron (1968), and Levison, Baron and Kleinman (1969).

Thus, rather than being strictly linear in nature, the operator's behavior was that of a quasi-linear element comprising linear, as well as, nonlinear features. Accordingly, the operator's total output, or response, could be described in terms of two components. A large component linearly correlated with the input, and a smaller but unrelated component. With respect to compensatory tracking activity, since the remnant portion of the subject's response, m(t), forms part of, and is also subtracted from the tracking input signal, i(t), to produce the perceived error stimulus, e(t), and furthermore, since the subject does not perceive the tracking input signal, i(t), nor his control output, m(t), directly, the remnant portion always contributes to tracking error if any response to anything but the tracking input is emitted. Thus, in a sense, the remnant portion circulates in the loop, reflects non linear operator behavior, and may be conceived as low amplitude white noise process injected into the system. Tustin (1947) proposed a linear model of the operator's tracking behavior which amounted to a conventional proportional plus integral controller multiplied by a pure time delay. Since this initial attempt,the majority of linear models that have been proposed may be characterized by a transfer, or describing function, that may be expressed as a rational fraction of polynomials multiplied by a time delay. Linear models have been expanded and refined to accommodate progessively more of the nonlinear features of the subject's output to the most recent,nine parameter,model of McRuer, Graham and Krendel (1967, in which adaptable and fixed neuromuscular parameters are separated. In its simplest form, however, a linear model of human compensatory tracking must incorporate at least two parameters. A gain, K,parameter representing the relationship between the size of displayed error and the size of the subject's response command, and a time delay parameter,τ,corresponding to the time elapsed between a control action,emitted at any one time, t, in response to an input occurring τ seconds before.

An important finding in Tustin's research,which both anticipated and paved the way for future findings showing the optimalizing behavior of the human controller,was that the operator adjusts his gain to a value such that the entire system, including himself, form a marginally stable system. Later,McRuer, Graham and Krendel, and Reisener (1965) found that for a wide range of controlled element dynamics,the operator's adaptive behavior is such that he can alter his control function to keep the dynamics of the entire man-controlled element system constant. Such 'equalizing' behavior for position, rate and acceleration controls is illustrated in Table 2.1.

The first column of the table represents the controlled element dynamics for proportional control (K_c), rate or velocity control $\frac{(K_c)}{s}$, and acceleration control $\frac{(K_c)}{s^2}$. These are, in turn, normally referred to as zero, first, and second order control dynamics. For a more detailed description of these orders of control see section 2.5.In these equations,s and s^2,respectively,represent the Laplace transforms corresponding to single integration (step function) and double integration (ramp function), in the time domain. The points of interest come from the second and third columns from the left. Firstly,in the second column,we note that the function describing the control behavior of the human operator changes with the controlled element dynamics so as to keep the form of the open-loop transfer function, describing the entire single-loop system, unchanged. This is evident from perusal of the third column of the table where the describing function $Y_p Y_c$ encompassing the human operator describing function, Y_p, and the controlled element dynamics, Y_c, are presented. Thus, when tracking with a direct linkage, proportional, K_c, controlled element, the operator performs

TABLE 2.1

SUMMARY OF HUMAN OPERATOR APPROXIMATE CHARACTERISTICS

CONTROLLED ELEMENT TRANSFER FUNCTION Y_c	APPROXIMATE HUMAN OPERATOR TRANSFER FUNCTION Y_p	OPEN-LOOP TRANSFER FUNCTION	
		FORM $Y_p Y_c$	EFFECTIVE TIME DELAY τ_e (sec) For the Example Pilot Subject
K_c	$\frac{K_p e^{-\tau_1 s}}{s}$	$\frac{\omega_c e^{-\tau_e s}}{s}$	NA
$\frac{K_c}{s}$	$K_p e^{-\tau_2 s}$	$\frac{\omega_c e^{-\tau_e s}}{s}$	0.14
$\frac{K_c}{s^2}$	$K_p s e^{-\tau_3 s}$	$\frac{\omega_c e^{-\tau_e s}}{s}$	0.43

a transformation on task-related information, conveyed by the error signal, so as to raise the dynamics of the entire system from proportional to rate. That is, if a given magnitude of tracking error is perceived, the error is integrated and the subject's output response is made in a direction that decreases the error, and of a magnitude proportional to the magnitude of the error. Accordingly, if the controlled element dynamics are changed to rate, $\frac{(K_c)}{s}$, the operator adjusts his behavior so as to maintain the rate dynamics and thus operates as a zero order, proportional, controller;where to a given magnitude of perceived error, a proportionally equivalent error reducing control action is emitted. Finally, if the output of the controlled element is integrated once more, $\frac{(K_c)}{s^2}$, to provide second order acceleration control dynamics, the operator then appears to behave as a differentiator, such that a step change in error velocity will be reflected in the operator's output as a step change in position only. The internal process whereby the operator transforms, or normalizes, the various input/output relationships so as to maintain the dynamics of the Y_pY_c system as those of a first order, simple integration, process, is referred to as an 'equalizing', or normalizing, process. Although, the Y_pY_c describing function given as

$$\frac{\omega_c e^{-\tau e s}}{s}$$

which McRuer and Krendel (1974) refer to as the 'crossover model' does not vary in form for the zero, first, and second order controlled element dynamics considered here, the various component values clearly differ in magnitude from one order of control to another. This point is illustrated in the fourth rightmost column of the table, where the effective processing delay parameter τ_e is found to increase, for the example subject, from 140 msec to 430 msec as the order of control is raised from first to second order. Moreover, although not indicated in the table, the ω_c parameter representing the crossover frequency, and which always incorporates the subject's gain as a factor (ω_c corresponds to the tracking input frequency at which $|Y_p Y_c| = 1$; Nyquist system stability criterion), is different for each of the controlled element dynamics. This is so,because as Tustin initially showed, the human operator adjusts his output gain to maintain system stability. Therefore, even though the open-loop crossover model can be shown to have a very considerable range of validity for a variety of Ss, tracking inputs, and controlled element dynamics, only the form of the describing function has such overall validity. Most of the components considered in the describing function, such as the $e^{-\tau_e s}$ pure time delay parameter encompassing sensor excitation (retina, cochlea etc.), nerve conduction, computational delays, and other, time consuming, data processing activities in the central nervous system, and the gain, K, parameter, may be modulated in complex ways to compensate for both the dynamics of the control, and inherent reaction-time delay. The describing function parameter adjustment rules cannot be stated simply, therefore, since they depend ultimately on interactions of the elements in the entire man-machine system.

For the single-loop compensatory system shown in Figure 2.1, involving an unpredictable tracking input, there are three task variables that have a major effect on the operator's tracking behavior: (1) the tracking input characteristics, (2) the controlled element dynamics, and (3) the actual control or manipulator used. (Many other factors are, of course, implicitly involved and include subject-centered variables such as training, fatigue and motivation. Although these are usually assumed to be constant and attempts to analyze them have been made, i.e. McRuer and Krendel, (1957), Chapter VII).

2.9. - Tracking a sum of sinudoids input: Effects of input bandwidth.

The most important aspect of the tracking input signal that affects the accuracy with which the subject can track it is the signal's bandwidth. The bandwidth of a signal is defined as the range encompassing the lowest and highest frequency present in the signal. In the compensatory tracking paradigm the tracking input signals are usually chosen to encompass very low frequencies, and the bandwidth of the signal specified as that of the highest cut-off frequency. Usually, the lower the bandwidth of a tracking input signal is, the better the subjects are able to track it.

If we ask the operator of a single-loop,feedback,system to track a single sine wave and examine closely the operator's response, we observe that the response includes the sinusoid tracked, as well as frequencies other than that in the input. The extra power at non-input frequencies represents the remnant discussed earlier and is due to both the failure of the operator to track the input perfectly, and strategies which he adopts to minimize tracking error. If we gradually increase the frequency of the sinusoid,at some point,the subject can no longer follow the track. The subject's inability to keep up with the input is not due only to structural limitations in the musculo-skeletal system executing the limb movements, rather,the limitation reflects central nervous system characteristics.

Fenn (1938), for instance, showed that the minimum period of free wagging of limb or finger is approximately 100 to 150 msec, and is presumably the lower limit for simple reaction time (Donders, 1868). When the tracking input is a low frequency sinusoid the subject can follow the sinusoid very well with little or no response delay (Poulton, 1950b), and can predict the input signal so that tracking can be carried out even when the subject's eyes are closed (Poulton, 1957c).

Doubling the frequency of a displayed,sinusoidally moving, point doubles its velocity and quadruples its acceleration. The corresponding effect of such a linear change in input characteristics on the subject's tracking error, however, is nonlinear. The relationship between normalized mean square error, (NMSE), (defined as the ratio of mean square error to mean square input amplitude) and the highest frequency in a sum of sinusoids random moving track was investigated by Elkind (1956). He noted that the complete relationship between average error and top track frequency component, or input bandwidth, was S-shaped. Subjects could follow the track with a compensatory display, with little appreciable increase in average tracking error amplitude for signal bandwidths up to 3.14 rad/sec. A steep increase in tracking error was then observed to follow further increases in signal bandwidth from 3.8 rad/sec. up to 10.7 rad/sec, where beyond 7.5 rad/sec, the subject, in attempting to track the signal, actually generated more error than that which would have been generated by the signal alone if he ceased to track it, keeping the control output, of course, to zero or near zero amplitude. Beyond 10.7 rad/sec, relative to the mean-squared amplitude of the input,the tracking error no longer increased as rapidly,since further increases in tracking input frequency would eventually reduce the contribution of subject's output to the error term in the NMSE measure ratio.

There are at least three distinguishable factors that may underlie increases in the average amplitude of tracking error with increasing input bandwidth: (1) the subject may not execute full corrective action tending to undershoot, or to overshoot,reversals in the track. Hence,relative to the amplitude of the input his response amplitude, or response gain K, may change with input signal bandwidth. Too much or too little gain would give rise to corresponding increases in tracking error.(2) the subject may not be able to prepare sufficiently for an imminent reversal in the track if he is already occupied in tracking another. Thus he may delay responding to the reversal until it actually occurs, incurring a further delay to his inherent neuromuscular response delay, or minimal reaction time. Increases in average response delay, τ, would therefore increase the amplitude of tracking error.(3) finally, the subject may, in failing to reproduce the input signal faithfully, include frequencies (including muscle tremor) in his response, unrelated to those comprising the tracking input, or tracking remnant. Elkind (1956) conducted a component analysis of subjects' tracking behavior and found evidence of selective changes in the parameters of gain K, response delay, τ, and remnant, η, with increases in input signal bandwidth. These changes were indicated by (1) a reduction in gain, (2) an increase in average response delay, and (3) an increase in the root mean-square (RMS) amplitude of the remnant. Changes in the K, τ, and η, parameters may be reflected singly, or in combination, as an average increase in tracking error. Therefore, simply noting that the requirement to time-share attention adds to tracking error, is informative only insofar as it indicates a decrement in task performance. This information may be valuable in an applied man-machine system engineering context where the requirement to divide attention may be considered a detrimental feature that ought to be either removed, or engineered around. But it can be of limited value only, because, as has been noted already, increases in overall tracking error may arise from factors other than the time-sharing of attention. Moreover, even if we do know at a more precise level of analysis that an increase in tracking error is mediated by changes in the three parameters, K, τ, and η, quite apart from other quite legitimate factors such as structural interference, fatigue, practice, and optimalization strategies being tested rationally by the subject (such as the well known bang-bang control oscillation in second order control), we may not reliably conclude that changes in these parameters reveal true attentional limitations.For instance, let us consider some possibilities that may underlie changes in the K, τ,and η, parameters with tracking input signal bandwidth that could reflect factors only indirectly related to attentional limitations in processing information.

An observed decrement in the gain parameter,K, with increases in tracking input bandwidth, for example, could have two origins. It could be due to the fact that at higher bandwidths, when reversals in the track follow each other more closely, the increase in the displayed magnitude of error corresponding to an uncorrected sudden reversal in the track,may once more begin to decrease after another reversal,so that the subject may not correct at all the error increase due to the first reversal. Alternatively, if the tracking input bandwidth is so high that the subject actually generates more error than that produced by the track alone, the controlled element movement may be deliberately reduced.

Increases in tracking input bandwidth also produced corresponding increases in the magnitude of τ and η. Such increases in the average response delay and remnant parameters,may be easily associated with corresponding increases in average reaction-time and response variability, or noise injection-- concepts readily identifiable in the literature of attention and thought to reflect, attentional, information processing, limitations with rate of input information (Wickens, 1976). The association is justified since, in effect, increases in the bandwidth of an otherwise random signal also increase its information content. A relative increase in, τ, from low input bandwidths to higher bandwidths, although consistent with limited-capacity single channel conceptions of attention may, however, reflect instead a reduction in subject's ability to infer, or extrapolate, (at least locally), the future activity of the track. If, for example, a reversal in the track occurs once every six seconds on average, the subject may be able to organize his response to the track an appreciable time ahead of an expected reversal, to reduce his response lag significantly. Whereas, if reversals in the track are more numerous, the subject may be less certain about his chances of anticipating correctly an imminent change in the track, lest the wrong decision be taken, and thus may wait for an actual increase in tracking error before correcting it. The corresponding increase in, τ, with signal uncertainty, could reflect limiting decision factors, rather than limiting factors usually attributed to single-channel operation, where only discrete amounts of incoming information may be handled at a time, the processing of all other information being delayed. Elkind's (1956) study, discussed by Poulton (1974 p. 125-6), provides good insight into the possible sources on an increase in τ with input signal bandwidth. Elkind found that when the subjects tracked low bandwidth, 3.9 rad/sec, inputs, average processing delay averaged only 10 msec. An increase in input bandwidth up to 10 rad/sec increased τ to 120 msec, and a further increase in bandwidth to 15 rad/sec produced a corresponding increase in τ up to 180 msec. The 180 msec average response delay observed is approximately the same as the mean RT to an expected visual signal. As the signal bandwidth is increased,the increased activity of the input increases the likelihood that an anticipatory response may be erroneously executed;increasing tracking error even more. Thus, the subject,expecting the signal to behave more or less as it does,waits rather for an increase in error to occur before reacting to it; the 180 msec average response delay being about half of that observed by Gottsdanker (1956a), to a sudden unexpected step in an irregular sine wave track. The initiation of responses in advance of an expected, though not necessarily imminent,reversal in the track could backfire on the subject,and increase rather than reduce tracking error, albeit temporarily. Moreover, if it so happens that on other occasions such an anticipatory strategy succeeds in reducing tracking error, overall tracking measures of error may or may not reflect such a 'gambling' strategy. The injection of responses not associated with the input signal would,therefore, increase tracking remnant, even though the subject's attentional limitations may well have not been reached; quite apart from factors which underlie an irreducible amount of tracking remnant (see page 43), and remnant induced by genuine attentional strategies and limitations.

2.5 Tracking with Proportional Rate and Acceleration Controlled Element Dynamics.

Control systems are usually represented as consisting of discrete interconnected blocks. The single-loop compensatory tracking system represented in Figure 2.1 consists of a display, the human operator, and the controlled element. Each of these elements of the system has an input and an output and therefore, in theory at least, the transformation on the input signal performed by the element can be represented by one or more differential equations. The mathematical model representing the transformation carried out by any element on its input is called the transfer function. The transfer function of any element in Figure 2.1 is simply the ratio of its output to its input (nonlinearities in the element being represented separately). Hence if the function of an element is only to provide amplification, then its transfer function is represented as a constant multiplier. Because representation of the input/output relationships involving several elements cascaded together, as in Figure 2.1 would involve the combination of several differential equations, and this in turn would imply integral transformation, such as convolution, it is usually simpler to use the Laplace transform of the differential equations rather than the differential equations themselves. This transformation enables computations to be done algebraically. The Laplace operator s may then be considered equivalent to the differential operator d/dt; 1/s to represent single-integration, $1/s^2$ double integration and so on. The order of control of a system is usually characterized by the number of pure integrations between the input and the output. Thus, if no integration is performed the system is identified as a zero order, proportional, control system. A system with a transfer function $1/s$, is a first order, rate, or velocity, control system, and one with a transfer function of $1/s^2$ is identified as involving double integration and is a second order, acceleration, control system.

A common manipulation in manual tracking studies is to vary the controlled element dynamics so that the operator is called to control either a zero, first, or second order system. Human beings, in their normal daily activities, are often controllers of zero, first, and second order systems. Riding a bicycle provides a simple example. The relationship between forward motion of the pedals and of the wheels represents a zero order, proportional control system, where a given size of bodily movement of the pedal produces a proportional movement of the wheels. The pedal is therefore a controlled element with zero order control dynamics. If the rider when coasting down a hill, for instance, wants to keep the speed of the bicycle constant, he can do so by applying the brake. In controlling the velocity in this way, the brake control dynamics are those of a first order rate system, where the speed of the bicycle depends on the position of the brake control lever. In steering the bicycle to the side of the road, the handlebar is an acceleration, or second order, control. The angular position of the handlebar determines the side to side acceleration of the bicycle, where the front wheel turns through an angle proportional to the amount of angular displacement of the handlebar, and the angle of the front wheel determines the rate at which the moving bicycle changes direction. In compensatory tracking, the dynamics of the control manipulated by the subject can easily be raised from zero, to first, to second order control by successive integration of its output. With no integration intervening, a bodily movement, c(t), of the control produces a proportional movement in the display. In a first order, or rate system, a nonzero output position of the control produces a rate change of movement on the display. Finally, in a second order system, a given nonzero output control position is integrated twice, producing an acceleration of movement in the display.

In terms of subjective tracking difficulty the human operator rates proportional control easier than rate, and rate easier than acceleration control. Poulton (1963a) and Regan (1960) showed that tracking with proportional control dynamics is reliably more accurate than tracking with rate controlled element dynamics. Garvey and Taylor (1959) and Holland and Henson (1956) also had shown that tracking is reliably less accurate with acceleration controlled element dynamics than with proportional element dynamics. A further study by Allen and Jex (1968) contrasting rate and acceleration controlled element dynamics showed reliable decrements in tracking performance, as indicated by an increase in relative tracking remnant, when moving from first to second order controls.

The subjective experience that progressively higher order of control dynamics are harder to track, is well founded, in that the rate of task information that must be processed also increases with order of control. But, unlike increases in information content due to increases in tracking input bandwidth, where the rate of input information is determined by the input signal, increases in task information content with increases in the order of control are determined by the dynamics of the control. Thus, the subject must also compensate for the constraints imposed by the characteristics of the control manipulated. Zero order proportional controls impose no constraints on the subject other than to exert some force to displace them. Once the displacement ends,the output of the control is constant. Higher order controls, however, are not so stable and once a displacement from a zero output reference is initiated the control output increases monotonically until the control itself is displaced back beyond its zero output, static, reference. Thus, the operator must compensate not only the magnitude of perceived tracking error, but must also adjust his controlling behavior to make the output of the control as nearly like the forcing function as possible. A rate control system, represented by a pure integration of a given step change in control output, inserts a phase lag of 90° in the operator's response, and halves the amplitude of his response every time he doubles his frequency. When tracking an acceleration control system, represented by two integrators in series, a 180° phase lag is inserted into the operator's control command, and reduces the amplitude of his response by a quarter whenever he doubles his frequency. Thus in tracking rate control dynamics, the operator's control movements have to lead the input by a phase angle of 90°. When tracking with acceleration controls, a phase lead of 180° has to be inserted. When the track is irregular and contains high frequencies, the subject must anticipate the tracking input well in advance, and without being able to see it directly. Thus, the higher the order of control, the greater the task uncertainty becomes. Hence, the operator can track better higher bandwidth inputs with proportional controlled element dynamics than he can with rate, and higher with rate than he can with acceleration. The limitations appear to be in both instances due to limitations in information processing capacity.

2.6. - Sensory Modalities and Displays

Although the majority of studies that have expressly examined the effect on tracking performance of divided attention between two or more concurrent tasks have involved visual presentation of tracking error, vision is by no means the only sensory modality which has been used for this purpose.

Hill (1970), for instance, provides a good review of tracking with tactile feedback information. In studies by Alles (1970) and Mann and Reimers (1970), in particular, error feedback was relayed to the human as tactile sensory information. The tactile display used was based upon the interesting phantom sensation phenomenon observed by Békésy (1957), who had initially noted that when two vibrators are placed on adjacent positions on the skin, a sensation is felt seemingly between the two. By selectively altering the relative phase and amplitude of the two vibrators, these researchers were able to provide subjects with both magnitude and direction feedback about controlling command movements (this signal was used to provide elbow-angle feedback for the Boston Arm Prosthesis). Gibbs (1954) and Noggle (1969) have also shown that subjects can perform compensatory tracking when error is relayed as kinesthetic feedback.

The viability of the auditory sense as an alternate input modality to vision, or as a supplement to it, has also been explored by Vinje (1971), Vinje and Pitkin (1972), and by Mirchandani (1972). These researchers noted that the auditory channel may, in certain circumstances, actually be superior to vision as an information gathering and processing device in human control. Auditory receptor delays, for example, have been found to be smaller than comparable visual receptor latencies (Woodworth and Schlosberg, 1954). Sinaiko (1961) and Wargo (1967) have also noted that response latencies to an auditory stimulus may be some 10 to 30 msec faster than comparable visual response latencies. Vinje and Pitkin (1972), on the other hand, did not observe faster auditory average tracking responses to an auditory analog of a visual compensatory tracking display.

Tracking an Auditory Display

Although numerous studies involving visual tracking have been conducted, relatively few studies have been conducted that involve the presentation of continuous, nonverbal, tracking error to the auditory sensory modality. The well known "verbal pursuit" tracking task, or auditory shadowing task, developed by Cherry (1953), so extensively used by psychologists in the 1960's in studying focused and divided attention, represents a very sophisticated process of information processing control. Though as much a transmission task (Posner, 1962; Fitts & Posner, 1967) as other more conventional manual tasks discussed earlier, due to the verbal aspects of the task it differs fundamentally from them. The shadowing task is essentially a symbolic, or semantic, pursuit tracking task where concepts rather than signal time-varying features <u>per se</u> are tracked. The shadowing task, however, may be used either as a primary or secondary task quite effectively in the study of attention. Cliff (1971), for example, examined the effect on visual compensatory tracking performance of time-sharing with an additional auditory shadowing task. In this study, input and response interference were well controlled, since neither the processing of input information,nor the response organization and execution stages involved the same sensory modality. Moreover,the nature of the tasks were sufficiently different to reduce the impact of an argument such as that proposed by Allport Antonis and Reynolds (1972),and seconded by McLeod (1977). The subjects tracked a first order control system whose forcing function input signal bandwidths were 0.94, 1.25, 1.71, 1.88 and 2.20 rad/sec. The shadowing task comprised verbal report of English prose. The subjects performed the tracking and shadowing tasks separately and in dual-task combination. Subjects performed one 5 minute trial run in each tracking input condition. Tracking error was found to increase monotonically with tracking input bandwidth. When the subjects performed both tasks together, the subjects found the combined tasks most demanding to perform,and on occasion, tracking control was lost and the tracking task had to be restarted. Cliff notes that such marginal stability in the tracking task was not present when only the tracking task was performed. Moreover, when the crosscorrelation function (see Page 97) relating the forcing function and the control output was examined, significant increases in average response delay were noted in dual-task relative to single-task performance. Cliff interpreted this increase in processing delay as due to single-input, limited - capacity, attentional information processing.

Perhaps the earliest research interest shown in man's ability to control a machine using auditory information was by DeFlorez (1936) who investigated the possibility of replacing visual displays by auditory displays during 'blind flight' operations. Later, Forbes, Garner, and Howard (1945), and Forbes (1946) extended this investigation using integrated auditory displays, where pilots were to fly only by auditory reference. Three types of display were presented to the subject. One of the displays indicated aircraft turn direction, to the right or left, by a corresponding tone initiated when the aircraft changed direction from straight ahead. A change in the pitch of the tone indicated whether the wing was being raised or lowered, thus providing information concerning aircraft roll. In a third integrated display the airspeed was indicated by the rate of interruption of the tone; the faster the rate of interruption the greater the airspeed. The research showed that pilots could, in time, make adequate use of the displayed information to fly the aircraft safely, but when the subject was to track the three displays he tended to track only one at a time, neglecting the other two. Apparently, tracking one of the displays was so demanding that there was little time, or attention, left to track the other displays. A recent, similar, well-controlled experimental study by Katz, Emery, Gabriel and Burrows (1966) also led to similar conclusions. These researchers concluded along with DeFlorez and Forbes that although auditory displays could be followed, replacing a visual display with an auditory display in an aircraft would generally lead to less accurate flying. Other evidence reveals, however, that auditory tracking may be carried out as accurately as its visual analog. For example, in a study by Humphrey and Thompson (1952), tracking error direction only (and not the more conventional magnitude-direction error display), was displayed as a 400 Hz tone that shifted from one ear to the other when the operator veered off target. When the joystick control was centered 'on target',zero error amplitude was indicated by an absence of the tone to either ear. This method of aural tracking was compared to a visual analog,where one of two lights was switched on,signalling left or right error. For both simple tracking inputs (2 cycles per minute sinusoid) and complex sum of sinusoids tracking inputs (combinations of 2 , 6, and 15 c.p.m. sinusoids) compensatory tracking was as good with visual as with the auditory type of display. In a subsequent study involving more complex tracking conditions, magnitude and direction of error were displayed either visually,or aurally,and a between modalities comparison was again made (Humphrey and Thompson, 1953). The aural display was a tone presented at equal amplitude in both ears for 'on target' (heard centrally between the ears) and which shifted position to either ear when 'off target', interrupted at a rate proportional to the error in displacement. Auditory tracking was inferior to visual tracking when error was displayed in the form of a spot on an oscilloscope. A major difficulty underlying this comparison, however, was that the subject was permitted to expand the visual presentation by adjusting a gain control, but a similar adjustment was not provided in the auditory tracking condition.

These studies did not consider the possibility of adding auditory feedback information to the visual task instead of replacing it. Mirchandani (1972) and Vinje and Pitkin (1972) investigated this possibility and found that displaying the tracking error to the subject over the visual and auditory modalities led to a reduction in average tracking error relative to a control condition in which presentation was only to the visual modality. Mirchandani required his subjects to time-share the control of a second-order, acceleration, compensatory tracking system, assigned as the primary task, with the concurrent performance of a secondary task involving the control of a velocity (first order) system, and using a different control stick. The display in both instances was visual. For the second order control system the display was a vertical line that could move from side to side from the centre of a visual CRT scope, and the manual movements of the stick were correspondingly left to right. The display for the secondary task was a horizontal line that moved up or down with backward-forward movements of the control stick about the centre of another oscilloscope display. When the subject controlled both systems at once on certain trials,the secondary task was also supplemented with an auditory display of the feedback information. The auditory display consisted of a single tone which could vary in frequency as well as volume, so that positive error was represented by a change both in frequency as well as in amplitude, and correspondingly, negative error was indicated by a lowering in frequency and an increment in volume from a 1250Hz zero error reference frequency whose amplitude was slightly greater than the threshold for human hearing. He found that when the subjects performed both tasks concurrently, average tracking error was found to be greatly reduced (for the secondary task only) when the additional auditory feedback was introduced, relative to a control condition in which it was not. Moreover, the variance of the average tracking error measure was also greatly reduced by the addition of the auditory display to the secondary task. Although not all the subjects showed an actual improvement in tracking the primary signal, there was evidence that some subjects did benefit from the reduced processing load in the secondary task. It is possible that the effect would have been more marked had his subjects been given more practice.

Vinje and Pitkin (1972) contrasted visual and auditory tracking performance using displays which would make the tasks analogous in every sense,other than the modality of input. Three subjects tracked random sum of sinusoids signals whose bandwidths were 1.7, 2.6 and 3.5 rad/sec, with either zero, first, or second order control dynamics. The auditory error display, e(t), was always linearly related to frequency; the sign of the error was assigned one to each ear (a one ear display was also investigated), so that the magnitude of positive error was indicated by corresponding changes in tone frequency, and negative error indicated by identical means in the left ear. The tone switched ears when the zero error reference was crossed. An analogous visual display was also used. Magnitude and sign were displayed as vertical movement of a point along one of two parallel paths. The path on the right represented positive error, the one on the left represented negative error. A zero error crossing was indicated by a change of the dot from one path to the other. Vinje and Pitkin found no appreciable differences between visual and auditory tracking. Their results indicated that the subjects could control equally well with visual as with auditory displays, provided that the same number of external references were available through each display (i.e., visual tracking performance was clearly superior to auditory tracking performance if the scope grid, or graticule, could be used to estimate the magnitude of visual tracking error more precisely). When the visual tracking error signal was also auditory ,in a combined display, so that the error signal was redundant between modalities, the combined display actually improved tracking performance. This effect was not reflected by a change in the average processing, τ_e, describing function parameter, although Wargo (1967), had noted that humans respond more rapidly to combined visual and auditory displays than to an auditory stimulus alone. One effect of increasing the order of control for both visual and auditory tracking alike, from zero to first, and to second order was to increase the average value of τ_e. Thus, the latency in human response is related to the complexity of the required response.

2.7.- Studies of Time-Shared Tracking

There are numerous studies of time-shared tracking in the literature. Often, a common recurrent finding in these studies has been that when an additional task is introduced, tracking performance deteriorates. Such time-sharing decrements have been observed when the additional task involved either discrete, or continuous information processing. Although the division of attention is a prerequisite in time-shared tracking performance, very frequently the time-sharing effects reported in most studies cannot be directly attributable to attentional limitations in multitask performance. Both within-modality interference and response interference are often uncontrolled factors in these studies; quite apart from other, perhaps equally important, factors such as practice, memory load, and motivation.

Within-modality interference is suspect in all time-sharing studies where multiple-task-related information is conveyed to the subject via the same sensory modality. (Where task-related input is presented to a different modality, time-sharing effects may not be attributable to within-modality interference.)

Unlike within-modality interference, response interference cannot be dismissed simply because responding manually to two concurrent tasks is shared between the hands. For instance, interference with tracking has been found even when the additional manual response is as minimal as that of releasing the pressure on a response button with the hand not involved in tracking (Elkind, and Miller, 1966), or pressing two keys to tones differing in pitch (McLeod, 1977).

Visual tracking performance has also been found to deteriorate with memory load. Johnston, Greenberg, Fisher and Martin, (1970) observed a decrement in visual tracking performance with zero order, proportional, control dynamics when subjects retained auditorily presented words in memory. Similar results are reported by Trumbo and Milone (1971) where subjects were to track and retain, in memory, either light or heard number sequences. Consequently, even when a study controls in part for both within-modality and response competition effects, time-sharing decrements may not, by default, be attributed directly to attentional limitations in information processing. Cliff's (1971) study, cited earlier, provides an excellent example of this. In this study, subjects performed a visual tracking task and an auditory shadowing task singly, and in dual-task, combination. Within-modality interference could be ruled out since task-related input was presented to different sensory modalities. Response interference can be assumed to have been minimized by the requirement to respond using different modalities (see also McLeod, 1977). Observing a decrement in tracking performance with time-sharing, which was attributable to an increase in average response delay, Cliff concluded in favour of single-input models of divided attention (Broadbent, 1958; Welford, 1959). He did not, however, consider the role that memory, as well as other factors associated with the auditory shadowing task (e.g., Underwood and Moray, 1971; Underwood, 1972, 1973, 1974), could have played in producing the observed time-sharing decrement in tracking performance.

Since within-modality, and response interference factors are so crucial in guiding our knowledge of human attention and performance, let us turn further toward some of the many studies which have observed time-sharing decrements in task performance that may be attributable perhaps more to these factors, than to genuine attentional limitations.

A. Within-Modality Interference

The reality of within-modality interference has not only been confirmed in the study by Treisman and Davies (1973) cited earlier, but it is also indicated in studies in which interference between a visual discrimination task and a visual tracking task occurred, even when the subjects were given explicit instructions to give priority to the tracking task (Allnutt, Clifford, and Rolfe, 1966; Benson, Huddleston, and Rolfe, 1965; Rolfe, 1966, 1967).

Often, the requirement to carry out incompatible information processing activities may be the underlying cause of within-modality interference, other than structural interference, or masking, *per se*. Evidence for this notion comes from studies by Pierce and Karlin (1957), and by Garvey (1950), and Garvey and Henson (1959). Pierce and Karlin, for instance, examined subjects' performance of a reading task while they attempted to keep a moving dot as close as possible to a vertical line that was presented alongside each word. Decrements in information transmission rates were found to accompany the requirement to time-share performance between these tasks. What proportion of these time- sharing decrements, central attentional limitations apart, could be attributable to mutual interference between habitual left-right eye-scanning patterns in reading,and eye-movement control associated with the visual tracking of a randomly moving dot, was not ascertained in this study.

Within modality-interference cannot be discounted in a study of the single-channel model of attention by Herman (1965). In this study,subjects were required to perform an auditory tracking task in conjunction with a discrete tone discrimination task. An attempt was made, however, to minimize obvious interaural masking effects (Fletcher, 1953).

The results of time-sharing studies in which within-modality interference is a controlled factor do not, however, clear up existing misconceptions concerning the nature of man's attentional process. The results are often both contradictory and inconclusive. Garvey and Taylor (1959), for instance, found no interference between a visual tracking task and an auditory discrete task. But that same year, Garvey and Henson, in another study, using the same zero order visual tracking task, and the same auditory digit subtraction task, did. Garvey (1960) in essentially the same study, but involving first order control, did not,however, observe such a time-sharing decrement.

In a more recent study, Wempe and Baty (1968) noted a decrement in the rate of information transmitted in a visual tracking task, with zero, first, and second order controlled element dynamics, when the task was performed in conjunction with a discrete tone discrimination task (see also Baty, 1971). A decrement in visual tracking performance was also observed by Watson (1972), when subjects performed the tracking task in combination with a visual digit classification task, or with a verbal reasoning task (Baddeley, 1968). Watson observed interference between the visual tasks, but not between the visual tracking task and the auditory task. Further support for the notion that within-modality interference may actually underlie time-sharing decrements in visual tracking,comes from studies by Glucksberg (1963),and by Wright, Holloway and Aldrich,(1974). Glucksberg showed that in a visual tracking task the addition of secondary tasks in auditory, or cutaneous, modes did not lead to a decrement in tracking, but the introduction of a visual task did. Wright, Holloway and Aldrich (1974) found that overall increases in visual tracking error followed the introduction of an additional visually presented verbal information processing task, but not if the same verbal material was presented auditorily. If the tasks are not sufficiently demanding of attentional capacity, however, time-sharing effects, arising otherwise from within-modality interference, may disappear when the performance of one of the tasks is changed to a different modality. This is quite a separate issue, however, from that relating specifically to central, limited-capacity theories of attention (Kahneman, 1973, Moray, 1967). If it is shown that by simply changing the modality of one of two otherwise competing tasks, a time-sharing decrement in performance is reduced or minimized, all this could simply mean is that: (1) within-modality interference effects were being eliminated, and (2) that the two tasks were not sufficiently demanding to produce a central time-sharing decrement between modalities. Nevertheless, such results have been used to support the notion of individual, modality-specific, capacity stores (McLeod, 1972).

B. Response Interference

Where within-modality interference may, or may not, be a possible underlying factor in studies which show a decrement secondary tasks in auditory, or cutaneous, modes did not lead to a decrement in tracking, but the introduction of a visual task did. Wright, Holloway and Aldrich (1974) found that overall increases in visual tracking error followed the introduction of an additional visually presented verbal information processing task, but not if the same verbal material was presented auditorily. If the tasks are not sufficiently demanding of attentional capacity, however, time-sharing effects, arising otherwise from within-modality interference, may disappear when the performance of one of the tasks is changed to a different modality. This is quite a separate issue, however, from that relating specifically to central, limited-capacity theories of attention (Kahneman, 1973, Moray, 1967). If it is shown that by simply changing the modality of one of two otherwise competing tasks, a time-sharing decrement in performance is reduced or minimized, all this could simply mean is that: (1) within-modality interference effects were being eliminated, and (2) that the two tasks were not sufficiently demanding to produce a central time-sharing decrement between modalities. Nevertheless, such results have been used to support the notion of individual, modality-specific, capacity stores (McLeod, 1972).

B. Response Interference

Where within-modality interference may, or may not, be a possible underlying factor in studies which show a decrement in tracking performance associated with time-sharing attention between two or more tasks, response competition often is an uncontrolled factor. In some studies,the source of response interference can be attributable to incompatible modes of responding. In McLeod's (1977) study, for instance, subjects performed a discrete tracking task,and a discrete tone discrimination task that also required organizing discrete responses with the hand not actively engaged in tracking. A good example of response interference directly attributable to the mode of responding, is that of studies by Benson, Huddleston and Rolfe (1965) and by Rolfe (1966, 1967). In these studies visual, rate control, tracking was carried out concurrently with a task requiring the subject to press one of two buttons associated to one of two lights. Both within-modality interference, and response interference could have caused the observed time-sharing effects. In this case, moreover, the response buttons were actually mounted in the tracking control stick and had to be pressed with the fingers of the hand doing the tracking. It is possible, therefore, that response interference could have been a major factor in producing the observed time-sharing effects.

Response interference has also been shown to be a major factor in two-axis, visual tracking, time-sharing decrements. Levison and Elkind (1967a) for example found that tracking along the x and y axes simultaneously produced greater tracking error when a single two-axis manipulator was used than when two single-axis manipulators were used. Yet, it should be noted that Levison and Elkind (1966) also found that after considerable training, subjects were able to perform two-axis tracking as well as they could single-axis using a single, two-axis, manipulator.

2.8. Tracking more than one loop simultaneously: Multiloop and Multiple Single-Loop Control Systems.

Whenever a subject performs two, or more, compensatory tracking tasks simultaneously, with separate displays and controls, the subject is said to be the operator of a multiple single-loop control system. A block diagram of such a system is given in Figure 2.2. An example of a multiple single-loop control system given by McRuer and Krendel (1974, p.40) is that of a pilot controlling both longitudinal and lateral stabilization of an aircraft in straight, wings level, horizontal flight using aileron and elevator controls. Studies of pilot behavior in multiple single-loop control in both flight and simulator settings are available (e.g., Hall, 1958, 1963; McRuer and Krendel, 1957; Newell and Pietrzak, 1968; Newell and Smith, 1969; Seckel, Hall, McRuer, Weir, 1957; Smith, 1966; Weir and McRuer, 1972).

When either the displays, or the controls, are combined into one, these kinds of system are known as multiloop control systems. Multiloop systems differ, therefore, from multiple single-loop control systems, in that in the latter there is no mechanical coupling; either between the displays or the controls. In Figure 2.2, the multiple single-loop control system represented contains elements relating to bimodal compensatory tracking. The visual and auditory sense modalities investigated are represented by the lower case letters v and a respectively. We note no coupling between the loops other than those internal to the human operator. Were there to be no coupling, either internal or external, the controller of such a system would be deemed a true parallel information processor. In multiloop control systems, where there is always some coupling, the assumption of true parallel information processing always implies the further assumption that the operator must first 'decouple' the loops. This assumption is often made in two axis tracking with integrated visual displays, so that an error marker may be free to move in any direction on the surface of the scope, some fixed distance from the zero-error reference. Researchers assume that the given position of the error marker is decomposed, or decoupled, into movement along the x and y axes. This would have to be the case if separate one-axis controls were allocated one to each coordinate. Whereas, when both the displays and controls are coupled, it is further assumed that after the x and y coordinates have been segregated and analyzed, the

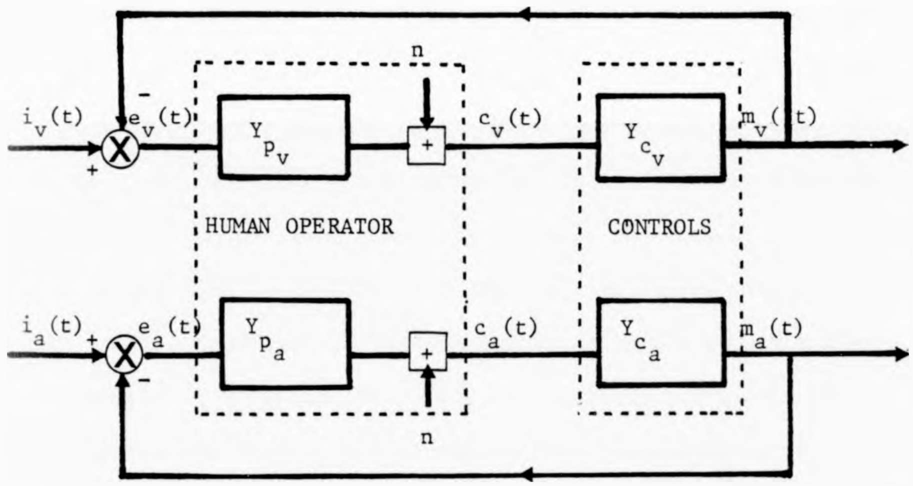

Figure 2.2. - Multiple Single-Loop Control System.

$i(t)$ = Forcing Function Signal.

$e(t)$ = Error Signal.

Y_p = Human Operator Describing Function.

n = Remnant Injected.

$c(t)$ = Operator Command Control Response Signal.

Y_c = Controlled Element Describing Function.

$m(t)$ = System Output Signal.

subject uses this information to organize an appropriate integrated error reducing response. There are further assumptions made in this coordinate analysis and synthesis process than may be agreed upon by everyone. For one, our normal visual experience of moving elements, is not always along strict x and y coordinates; and hardly ever are we required to control them so. If it becomes possible for the subject to establish one-to-one mappings between the position of the error marker and the position to which he should displace the control, the dual-task may, in time, become in reality a single task; much like tracking a moving object with binoculars (hardly a dual task). It is possible therefore to argue that whenever it is shown that after considerable practice subjects can track an integrated display/controls,two-axis,system as well as a single-axis one (Levison and Elkind, 1965), the subjects have in fact learned to integrate the dual-axis task into a single task. Hence, only one input, and one output, may be involved as far as the subject is concerned. The multiloop system may become to the subject,a single-loop system. Thus, the assumption of true parallel information processing may not fully be warranted in multiaxis conditions such as these. Nevertheless, Levison and Elkind, observed that although the single-axis, dual-axis, tracking condition contrast was not statistically significant, two-axis relative tracking error was some 10% greater than that for one-axis tracking.

Considerably more support for the notion that subjects may indeed be able to control multiple single-loop systems in parallel, comes from studies by Levison and Elkind (1967), and Todosiev, Rose and Summers (1966). Todosiev, Rose and Summers found no difference in normalized mean square tracking error NMSE between single-axis ,and dual axis ,tracking conditions. Input bandwidths of .2 and 1.0 rad/sec had no appreciable effect upon this relationship. Levison and Elkind also investigated one and two-axis tracking conditions, with separate displays and controls, as a function of input bandwidth. Random, low frequency, signals generated by summing 17 sinusoids with corner frequencies of .5, 1.0, and 2.0 rad/sec were used. The results again showed no reliable difference in tracking NMSE between single-loop and multiple single-loop control for the three input signal bandwidths considered. Ziegler (1968), however, referring to these two studies, noted that if a single-axis, dual-axis difference in NMSE was not found, it could have been because the tracking tasks were not sufficiently demanding when performed concurrently. To produce a time-sharing decrement Ziegler investigated the effects on one-axis tracking of introducing a second axis. The single-task and dual-axis, tracking conditions were examined with zero, first, and second order controlled element dynamics. The results showed significant increases in tracking error in the dual-task relative to the single-task tracking condition. Although, such a time-sharing decrement in performance was present in all instances, only when tracking involved first, and second order controls, was this time-sharing effect statistically significant.

A. Multiple Single-loop Control with Homogeneous and Heterogeneous Inputs and Control Dynamics.

Although there is some controversy concerning the issue of serial vs. parallel information processing in the one axis, two-axis tracking literature, there is no disagreement with the replicated effect that tracking performance on a single-axis task is considerably reduced by the addition of another axis with different dynamics (Chernikoff, Duey and Taylor, 1960; Chernikoff and Le May, 1963, Levison and Elkind, 1967). Whenever the controlled element dynamics differ between the tracking loops, the control system is said to be a system with heterogeneous dynamics. A heterogeneous inputs system, on the other hand, is created whenever the various statistics that describe the forcing function input signals differ from each other.

Chernikoff, Duey and Taylor (1960) found that tracking error in a given loop increased with the discrepancy in control dynamics between the loops. Homogeneous controlled element dynamics were found to yield lower tracking error values. When the control dynamics in one loop were zero order and first order in the other loop, overall tracking error was greater than with zero order control in each loop, and lower than that with zero order control in one loop and second order control in the other.

The discrepancy observed between dual-axis homogeneous dynamics and dual-axis heterogeneous dynamics is thought to reside in the requirement to establish two qualitatively distinct transfer functions, one for each control loop, when the control dynamics are heterogeneous, but not when they are homogeneous. This is because as McRuer, Graham, Krendel, and Reisener (1965), found, the subject alters his transfer function so as to keep the entire man/machine system describing function as that of a first order system. Thus, when controlling a zero order system with one hand and a second order system with the other, the equalizer characteristics will have to be such that the transfer function representing the man in each loop will be that of an integrator in the former, and that of a differentiator in the latter. Presumably the information load thus generated is much greater than that which arises when homogeneous transfer functions have to be maintained.

The establishment of two distinct equalizer characteristics in heterogeneous control systems does not seem to be carried out, in parallel, without interference. Levison and Elkind (1967) noted that the describing function on a zero order loop appeared to adopt some of the characteristics of the describing function in the other, second order, loop. Such linear crosscoupling between the loops in multiple single-loop control has also been reported by Van Lunteren (1977) with homogeneous control dynamics.

Apparently, the requirement to establish quantitatively distinct equalizer characteristics with heterogeneous inputs does not increase tracking NMSE (Levison, 1966). The establishment of distinct equalizer characteristics when the input signals, rather than the control dynamics, are heterogeneous, implies that only the bandwidth of the control movements must be organized separately. The loading thus induced on the response execution stages, ought to have been indicated by a significant increase in tracking NMSE. This ought to have been the case,if response interference is a major contributing factor of error in time-shared tracking performance.

In order to investigate some of these issues and in order to establish whether time-sharing decrements associated with bimodal multiple single-loop control are central, reflecting genuine attentional capacity limitations, a research program of four related experiments was conducted.

CHAPTER 3

DESCRIPTION OF EXPERIMENTS AND COMPONENT ANALYSIS OF TRACKING

3.1. - Introduction to the Experiments

Four experiments were conducted in which there were two main variables, the forcing function signal bandwidth and the controlled element dynamics. The bandwidths explored were .48, .86, and 1.84 rad/sec, and the plant dynamics were either zero, first or second order control.

Subjects performed visual and auditory continuous compensatory tracking tasks under focused and divided attention conditions, with correlated and uncorrelated random inputs of various bandwidths, and with various controlled element dynamics. In Experiment 1, the forcing function signal bandwidth was the major experimental variable. In Experiment 2, the order of control was manipulated. In Experiment 3, the forcing function signal bandwidths in each tracking loop could be homogeneous (the same) or heterogeneous (different), and the homogeneity of the control dynamics was a constant. In Experiment 4, the bandwidth of the forcing functions was homogeneous and held constant, while the degree of homogeneity in control dynamics was experimentally manipulated.

The rationale behind the experiments was simple. In all the experiments, the effect of time-sharing on tracking performance was investigated. In Experiments 1 and 2,a straight application of the time-sharing paradigm was carried out. Subject's performance in a given visual, or auditory, tracking task was related to the performance of that same task when the visual and auditory tracking tasks were performed in dual-task combination. When performing both tracking tasks, in multiple single-loop control fashion, subjects were told to treat no one particular tracking loop as primary. In Experiments 3 and 4,the time-sharing paradigm was extended in order to investigate the effect,on the performance of one of two concurrently performed tasks, of selectively varying the information processing demands of the other task. In Experiment 3, subjects tracked forcing functions that could be equal,or different,in signal bandwidth. In Experiment 4, subjects also performed visual and auditory tracking simultaneously, but the dynamics of the joystick controls manipulated could either be the same,or different,with respect to order of control.

A salient methodological innovation in these two final experiments relates specifically to the time-sharing paradigm and deserves a few introductory remarks. The time-sharing paradigm obtains its power from the fact that by examining the subject's performance of a single task in isolation,and again when it is performed in conjunction with one or more additional tasks, it is possible to determine to what extent various task combinations interfere with the performance of the task. A more or less precise formulation of attention is thus possible. Because the technique enables the establishment of logical relationships crucial to the understanding of the many distinct facets of human attention and performance, it has recently raised to the status of a very powerful technique (see Kerr, 1973, & also Rolfe, 1971 for a historical overview and application). The technique, however, is open to the criticism that the single-task condition may not actually be an adequate control condition (e.g., Maynatt, 1977, Moray, 1969); one obvious reason being the presence of effects directly associated with dual task performance, and not so attributable to attentional limitations. In Experiments 3 and 4 of this thesis, an extension of the time-sharing paradigm was developed in which the performance of one of two concurrently performed tasks was related to performance of that same task, contingent on experimental manipulation of the other task. By noting to what extent the performance of one of two concurrently performed tasks depends on information processing manipulations of the other, we have a new and considerably more powerful method of studying divided attention that is free from single-task /dual-task assumptions and considerations.

Although the bandwidth, and order of control variants used in Experiments 1 and 2 were meant to vary selectively the informational load associated with the performance of the visual and auditory tracking tasks, they were also meant to tap, or probe, distinct information processing activities. We have noted earlier in Chapter 2 that increases in forcing function bandwidth produce corresponding increases in the rate of incoming information, whereas, increases in the order of the control dynamics, imply differential changes in the nature of the transformation carried out on input information. Increasing the bandwidth of the forcing function signal only implies quantitative changes in the transfer function parameters, whereas, qualitative changes in the human's transfer function are implied by adaptability, or by the establishment of equalizing characteristics, to different changes in control order (McRuer, Graham, Krendel and Reisener, 1965). By bandwidth and order of control manipulations, it is possible, therefore, to examine (1) whether the rate of incoming information, or (2) the nature of the transformation carried out on the input signal, give rise to either quantitatively or to qualitatively different effects on time-shared tracking performance.

In Experiments 3 and 4 one major aim was to establish and test the hypothesis that the attentional information processing capacity allocated to enable the performance of a given task, depends on the total information processing demands imposed by the tasks on a central limited capacity information processing system (Kahneman, 1973; Mcray, 1967). That is, according to the undifferentiated capacity hypothesis, the performance of a given tracking task will depend on the amount of available attentional resources, or capacity, that can be allocated to it. This view is in contrast to another, which postulates that the amount of attentional information processing resources allocated to a given task is fixed, and depends on the intrinsic information processing characteristics of the task being performed (Kerr, 1973; Posner and Keele, 1970). According to this view, the performance of a given task will be found to be more or less independent of that of another task performed concurrently with it, provided, of course, that total capacity limitations are not exceeded. An undifferentiated capacity account, on the other hand, implies that when two tasks are performed concurrently, there will always be less attentional capacity left over to carry out the tasks than when only one task is performed by itself. If it is assumed that at some ultimate level, the total capacity available for the performance of two simultaneous tasks is a constant, then it is possible to relate task performance to the relative proportion of capacity allocated to each component task, and may thus be interpreted in terms of a general principle of complementarity (Norman and Bobrow, 1975). Along similar lines, by assuming that the total capacity is allocated proportionately among the various information channels, and further, that the amount of noise injected into any given channel scales with the variance of the signal being processed, Levison (1969) proposed such a quantitative,predictive,model of task interference. More recently, Levison Elkind and Ward (1971) attempted to test further the validity of such a model in the context of two and four-axis compensatory tracking and noted that although it provided a good fit to the measures of tracking error observed, the actual allocation of capacity (indicated by an equivalent observation noise ratio on each task) departed considerably from predicted optimum values in both the two and four-axis cases. These researchers suggested that task interference was attributable to a decrease in tracking linearity,but not to some other parameter such as processing delay. The assumptions of constant capacity and information processing channel equivalence,in such models,may not be entirely warranted (e.g.,Kalsbeek and Sykes, 1967; Kahneman, 1973; Kantowitz and Knight, 1976). Kahneman (1973) for instance noted that available capacity may change as a function of task demands. Moreover, Kantowitz and Knight (1976) have also noted the possibility that the attentional allocation system may be conservative so that full resources are not allocated and some spare capacity always remains. In any event, and perhaps even in spite of an upper limit on attentional resources,it may be possible to show that the performance of a given task depends on what other irrelevant and distracting information processing activities the subject may be concurrently engaged in.

Since in multiple single-loop compensatory tracking systems the subject does not view the forcing function signals directly, it is possible to conceive of a situation in which identical forcing functions may be used to drive the various control loops, and hence the man be required to track two otherwise correlated signals. Given that some remnant, as well as variability in average response delay and response amplitude, may compound to alter the displayed tracking error signals it cannot be argued that the error signals would, by default, be identical. By introducing some of these correlated input trials among trials in which the forcing functions are not so related, it is possible to determine (1) the impact upon time-shared tracking ability of processing correlated signals, and (2) whether in controlling a multiple single-loop system, whose tracking loops impose simultaneous information processing, error reducing, demands, the human controller behaves as a serial error reducing system, or not. In all the experiments, therefore, the correlation coefficient relating the absolute magnitude of tracking error, disregarding its sign, was examined. It should be pointed out, that for the purpose of distinguishing between serial and parallel error reducing activity, in multiple single-loop control, it is immaterial whether the forcing functions driving the system be correlated or not. This is because the subject's task is to reduce the magnitude of perceived error in each loop. Therefore, for a true parallel information processing system the fact that error buildups may occur more or less in synchrony between the loops is inconsequential. To a serial system, however, it is not, because unless mounting error in each loop is reduced as it occurs, reducing tracking error in one loop,and not in the other,inevitably leads to inverse relationship in absolute tracking error magnitudes between the loops.

Since there is always the possibility that when subjects are set to track the correlated forcing functions they may simply ignore one of them, and track the other,while copying with the hand not actively engaged in tracking every single error reducing movement made, the following control task was designed. Subjects were required to track the visual,or the auditory,input,while simultaneously copying the movements of the tracking hand with the other hand, using another identical control. Hence, in this condition, the subjects were required to emit two simultaneous responses to a given single error signal. Moreover, note the implication of such a task with regards to the issue of response interference effects in time-shared tracking discussed in Chapter 2. If it were to be the case that the requirement to organize and execute simultaneous dual-task responses to one input produced as much of a time-sharing decrement in tracking as that involved in processing two inputs, then it could be justifiably argued that such a time-sharing decrement was directly attributable to response interference. If on the other hand,response interference effects should not be sufficiently great to account for any observed time-shared tracking decrement, then such a decrement could perhaps reflect genuine attentional information processing limitations.

Since an observed increase in overall tracking error associated with time-shared tracking would only indicate some form of multitask interference, a component, time domain, analysis of both tracking linearity and average response, or processing, delay was carried out. The computational steps involved in obtaining the various measures of tracking performance constitutes the remainder of this chapter. Moreover, in order to enable suitable coding of the various visual and auditory, single and dual-task conditions,a special terminology was designed. The details of this convention are given at the very end of the chapter.

3.1.- Tracking Performance Measures Used

Normalized Mean Squared Tracking Error (NMSE)

The mean-squared tracking error in each single-loop was normalized with respect to the mean-squared tracking input. The NMSE measure is defined as:

$$\text{NMSE} = \frac{\dfrac{\sum_{m=1}^{m=N} e^2_m}{N}}{\dfrac{\sum_{m=1}^{m=N} i^2_m}{N}}$$

e is the amplitude of the error signal, i the amplitude of the forcing function and N is the number of data samples. Tracking NMSE is taken to be inversely related to efficiency of tracking performance. Since the data collection interval, during each tracking run, was 51.2 secs., and the forcing function(s) and system output signal(s) were sampled at a rate of ten per second, 512 sampled data values were then averaged in the calculation of each mean-squared statistic.

Tracking Linearity, R_{max}, and Average Processing Delay, τ, Measures.

The better the subject tracks, or follows, the forcing function input signal, i(t), by appropriate manipulation, c(t), of the control, the more the output of the controlled element, m(t), resembles the forcing function (input). Hence, the system input and output signals will be positively correlated in time, but only maximally so, when the phase lag between these signals is minimized. By successively shifting and correlating the two signals in a direction which reduces their relative phase lag,it is possible to ascertain both (1) the time difference between the presentation of the forcing function,and the subject's control output signal emitted in response to it, and,(2) the degree of correspondence, or tracking linearity, between the two signals. This successive shifting and correlating process between two signals produces a function in time known as the Crosscorrelation Function. The two signals are thus compared and are said to be linearly related, or correlated, if the Crosscorrelation Function at any one time has a value significantly different from zero.

The Crosscorrelation Function for two discrete time functions x(t) and y(t) is given by:

$$R_{xy}(\tau) = \frac{N\Sigma x(t)y(t+\tau) - \Sigma x(t)\ \Sigma y(t+\tau)}{\sqrt{\{N\Sigma x(t)^2 - (\Sigma x(t)^2)\}\{N\Sigma y(t+\tau)^2 - (\Sigma y(t+\tau)^2)\}}}$$

where τ is an integer scalar in the range $-N<0<+N$

and $N = N-\tau$ sampled data pairs

The Crosscorrelation Function represents, therefore, a special time average of the product of two time functions.

Both the concepts of input/output linearity, and relative lag, in continuous tracking can be associated with response variability, and response delay, in discrete reaction-time information processing tasks (see Wickens, 1976 for a discussion). The crosscorrelation peak value, R_{max}, moreover, since it relates specifically to the component of the subject's response which is linearly correlated with the forcing function input, also provides, by default, information concerning any non-linear components that may also be present in the signal. Thus, if the requirement to time-share tracking leads to a decrement in the R_{max} coefficient, a corresponding increase in tracking remnant, η, is directly implied.

Although, there is an obvious similarity between discrete reaction-time to a stimulus, and responding in a tracking task, there is good reason to believe that the association between mean RT and τ measures should be made cautiously. One of the major difficulties in making a strong association between discrete reaction-time and continuous processing delay, is that in tracking tasks it is difficult to isolate, exactly, corresponding stimulus-response pairs. Another difficulty is that of a lack of a simple criterion of predictability that could serve as a basis for ranking signal input stimuli. Nevertheless, to a first order of approximation, τ may be considered, in many ways, an analog correlate of discrete reaction-time, since both τ and mean RT appear to be tapping the same internal processing time. Conclusive inferences about the relationship between

τ and RT cannot at present be made. For example, although Jex and Allen (1970) have not always observed a direct correspondence between τ and RT across subjects, Pew and Rupp (1971) observed that the developmental decrease in discrete RT with age initially recorded by Phillips (1935), fitted very closely to comparable developmental changes in τ.

Correlating the absolute tracking error signals in bimodal compensatory tracking.

In order to ascertain the functional relationship between the absolute tracking error signals in simultaneous visual and auditory tracking conditions, the tracking error signals $e_v(t)$ and $e_a(t)$ were sampled simultaneously and the sampled data pairs were correlated. The tracking error signals were sampled at the rate of 10/sec for the 51.2 sec data collection period of each 71.2 sec tracking run. Thus 512 sampled data pairs were involved in the computation of the Pearson Product Moment correlation coefficient. Since only the absolute magnitude of tracking error, and not its sign, was of theoretical relevance, the elements in all tracking error pairs were arbitrarily chosen to be positive in sign.

Interpreting the correlation coefficient between absolute tracking error signals: a theoretical caveat.

In interpreting the correlation coefficient, r, between two variables ,the assumption is made that the fitting of two straight regression lines to the data does not distort ,or conceal,the functional relation between the two variables. For example, if a curvilinear relationship between two variables exists, whereby fairly accurate prediction of one from the other can be made, when fitted with two straight regression lines, the lines may be found to lie more or less at right angles to each other. The correlation coefficient therefore, could well be zero, or near zero, despite the strong, but nonlinear, relationship between the variables. Thus, even though a true random relationship will always show a zero correlation, the converse is not true. A zero correlation value does not always imply a true random relationship.

With respect to the relationship between the absolute tracking error signals generated by the controller of a multiple single-loop compensatory tracking system, there is of course no reason to assume a priori that a strictly linear functional relationship should exist between the signals. Yet the inverse relationship in tracking error predicted by an all-or-none information processing models of attention assume this. This is because in a time-shared,continuous,compensatory tracking task, the subject is required to minimize tracking error continuously. The drawing away of attention from one loop, to give it to another, implies, therefore, an increase in tracking error in the unattended task, and a corresponding decrease in error in the task receiving attention. Such an inverse relationship between the error signals is characterized by a negative correlation coefficient. Although knowledge of the nonlinearities that may be shown to exist between the absolute tracking error signals may some day prove of heuristic value in the development of more representative models of attention, for the time being, the presence of significant negative correlations between the signals is all that is needed in order to support an all-or-none information processing model of attention in continuous, bimodal, multiple single-loop control.

Linear correlation between the operator's control command response signals $c_v(t)$ and $c_a(t)$: An analysis of crosscoupling between the loops.

A decrement in multiple single-loop control performance, relative to single-loop compensatory tracking performance, cannot be ascribed to the requirement of time-sharing attention between the loops, until it is shown that motor interference, or improper response differentiation, are not contributing factors. These two factors are distinguishable as either (1) an injection of noise, or remnant, arising from changes in neuromotor activity (due to increased coordinated response load), and increases in response variability between the loops due to crosstalk of motor commands.

That is, a control command selected for one hand may not entirely be segregated to that hand, but may also be reflected in the response made by the other tracking hand. The distinguishing feature between these two possible sources of controller remnant is that in the former, the remnant is unrelated to either tracking input. Whereas, in the latter, variability in the operator's response to one input might also incorporate another component comprising involuntary responses to the other input.

There is good reason to believe from a recent study by Van Lunteren that each single-loop in a multiple single-loop control system is not totally free from crosscoupling from other loops. Van Lunteren (1977) tested this assumption and observed linear crosscoupling between two otherwise independent visual compensatory tracking tasks. The effect was very small, however, and was interpreted in part as arising from the visual display configuration used in the study, and also in terms of central crosscoupling in the motor system. Because the linear crosscoupling term in the transfer function was negative in sign, a tendency for the hands to move in opposite directions was implied.

One approach that can be taken in order to determine whether a reduction in task performance associated with the requirement to divide attention between two otherwise independent manual tracking tasks arises from crosstalk between the hands is to examine the linear relationship between the operator's response commands to one loop,and the input to the other loop. Another, is to simply examine the crosscorrelation function relating the operator's control command signals. Since the displays used in these experiments involved the visual and auditory modalities, instead of only the visual modality, we can discount the notion that visual display configuration factors underlie the effect. If the linear crosscoupling reflects itself as a tendency for the subject to emit low amplitude mirror image responses to the forcing function input signals, provided the input signals are uncorrelated, any such tendency should be detectable as a negative correlation peak in the crosscorrelation function relating the subject's manual responses $c_v(t)$ and $c_a(t)$. Such an analysis was conducted in Experiments 3 and 4.

TERMINOLOGY.

In Experiments 1 and 2,subjects performed visual and auditory compensatory tracking tasks separately,and in conjunction. When the visual and auditory tracking tasks were carried out concurrently, the forcing functions could be either identical or unrelated. In addition,subjects were also required to perform visual,or auditory,tracking tasks with an additional copying task.

Thus, six different tracking conditions were involved. Single-task conditions were termed VISUAL and AUDITORY (for the sake of presentation, in both tables and figures, the RY letters in AUDITORY were left out) tracking conditions. Dual-task conditions involving either correlated or uncorrelated input signals were termed BOSAME and BODIFF respectively (contractions for 'both inputs same', 'both inputs different'). Those involving the additional copying task were termed respectively VICOPY and AUCOPY. This terminology applied throughout the entire experimental program.

CHAPTER 4.

4.1. - Experiment 1: Effect of Forcing Function Signal Bandwidth.

The object of this experiment was to examine the effect of forcing function signal bandwidth on a subject's performance of a visual or an auditory compensatory tracking task under single-task, and time-shared tracking conditions.

There were three main questions of interest to which the experiment was addressed. The first concerned whether the requirement to divide attention between concurrently performed tasks is, or is not, of consequence to the performance of either of the tasks. The second question, relating directly to the first, was concerned with the dynamic characteristics of the process underlying the presence, or absence of an increase in tracking error directly attributable to time-shared tracking. Knowing that an increase in tracking NMSE may, or may not, follow the requirement to time-share tracking, does not in itself enable drawing reliable inferences about the dynamics of man's attentional process. The experiment, therefore, sought to establish whether the human operator engaged in bimodal compensatory tracking, behaves as a serial, or parallel, error reducing information processing system. The third question of interest concerned the relative contribution of the various factors that may underlie time-sharing increases in tracking NMSE. If it were to be the case that in performing the visual and auditory tracking tasks concurrently, tracking NMSE in either task showed a relative increase with respect to single task performance, we would still not know whether such an increase in NMSE arises directly from either increases in average response delay, decreases in overall tracking linearity, response gain, or in effect, any combination of these three factors. The third and final question was concerned with the role played by response interference in producing such effects. Even if it were shown conclusively, for example, that time-shared tracking increases arose directly from an injection of remnant, or from an overall increase in processing delay or perhaps, even from the interplay between these two variables, we would still not be able to claim central attentional limitations without ascertaining first the relative contribution of response interference factors. The following experiment aims to overcome these problems:

METHOD

Subjects:

The subjects were twelve students from the University of Stirling. All the subjects were right handed and reported normal hearing and vision. Subjects ranged in age from 17 to 25 years.

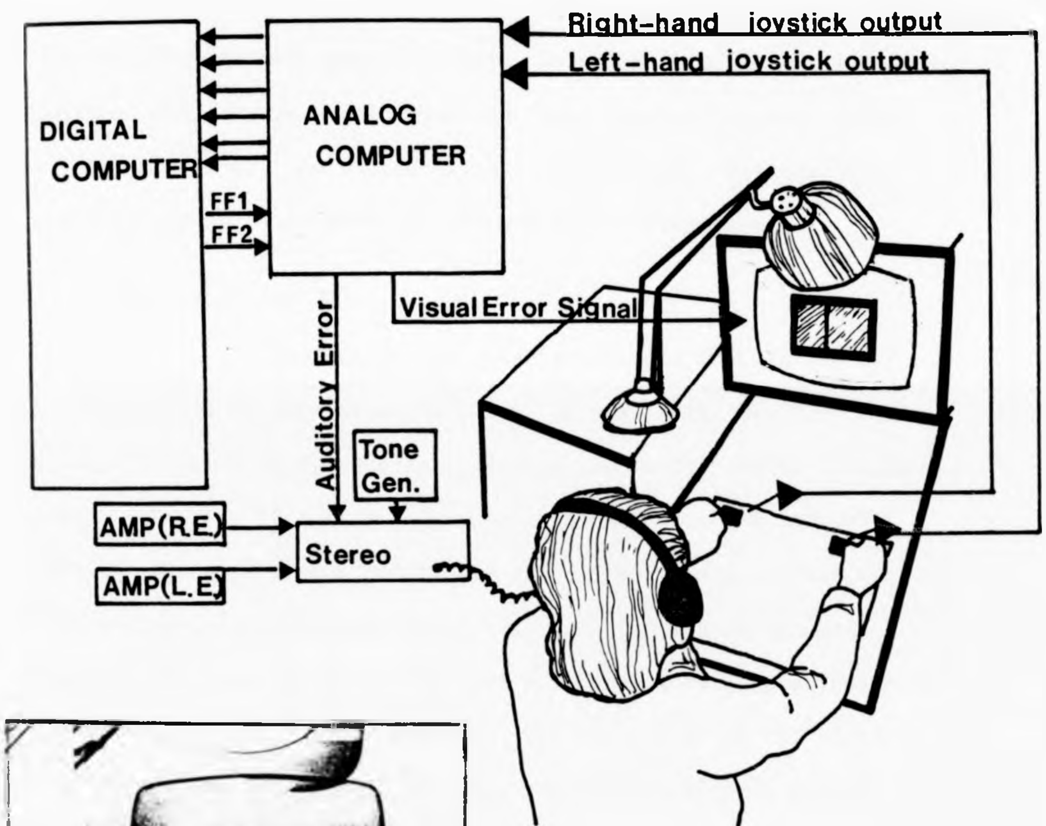

Figure 4.1a

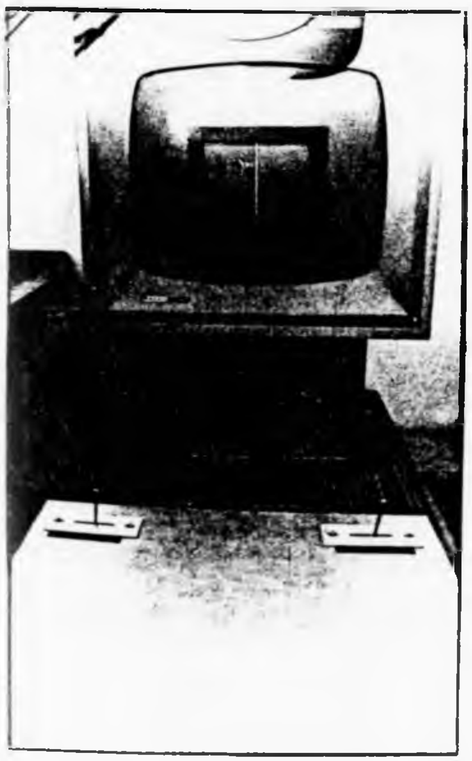

Figure 4.1b

All the subjects were paid £0.60/Hr. In order to encourage subjects further, subjects were told that the 'best tracker' in each group of subjects, i.e., the subject with lowest overall tracking error, would receive a £2.00 bonus at the end of the experiment.

Apparatus and Materials

The subject sat at a table facing a CRT display oscilloscope set at approximately 0.5 m at eye level (see Figure 4.1a). In front of the subject, also on the table, was an aluminium casing measuring 48 x 41 x 5 cm upon which the joystick controls were set 33 cm from each other, and 5.5 cm from the far edge (see Figure 4.1b). Each joystick consisted of a thin 2.5 mm diameter cantilevered, circular steel rod that projected 4 cm perpendicular to the surface of the casing, and which was affixed below the surface to the turn rod of a single-turn low friction conductive plastic potentiometer (See Appendix A). Each joystick could be moved 70° to either side from vertical along a slit, with a maximum arc deflection of 10 cm before reaching stops. The joysticks were not spring-loaded. Whenever one of the joysticks was moved from an upright vertical position to the right, or to the left, a change in voltage was induced. Moving the stick all the way to one side from vertical, until the stop was reached, produced a change in voltage from 0 Volts to 10 Volts. The sign of the voltage was positive when the joystick was moved to the right, and negative when it was moved to the left. To provide rate control dynamics in each tracking loop the output of each joystick was integrated once at a rate of 1 Volt/sec. (See Appendix B). Integrator units in an EAI analog computer were used for this purpose. The integration process was electronically locked by a diode circuit beyond the ± 10 Volt operating range. The output of each integrator, or system output, was subtracted from the forcing function to obtain the tracking error signal. The error signal from each control loop was then displayed to the subject.

Forcing Functions

The forcing functions, or tracking inputs, were made available at run-time by a program implemented in a PDP 11/45 digital computer. The discrete functions generated by the program were transformed into continuous functions of time by means of digital to analog conversion, and were scaled by means of an analog computer, to operate within a ± 10 Volt range.

The forcing functions were low frequency pseudo-gaussian noise signals generated by summing 10 sinusoids whose frequencies were respectively .25, .37, .49, .61, .86, 1.47, 1.84, 2.58, 3.56, 4.79 rad/sec. Levison's (1975) recommended procedure for generating tracking functions in manual tracking research was followed. Orthogonality between the component sinusoids was assured by choosing the sinusoids so that an integral number of cycles of each component was contained in a fixed 51.2 sec. measurement interval. Each sinusoid was therefore harmonically related to the fundamental frequency ω_o where:

$$\omega_o = 2\pi/51.2 = .123 \text{ rad/sec}$$

The amplitudes of the various component sinusoids were the same, giving a rectangular spectrum up to the cutoff frequency, augmented by a low-amplitude shelf containing 5% of the total signal power, and which extended to the highest frequency component. The bandwidth of the signals specified by the cutoff frequency were .49, .86, and 1.84 rad/sec. All the forcing functions were normalized to an arbitrary 4.81 cm measured RMS deflection on the scope.

In order to provide more than one forcing function in each bandwidth condition, and to equate them with respect to overall tracking difficulty, each of the forcing functions was reversed in time, reversed in sign, and time and sign reversed to yield four different yet statistically identical forcing functions. In order to enable the subject to be involved in tracking the signal well before the measurement interval began, a 20 second segment from the beginning of each signal was time reversed and appended at the beginning of the signal. The phase characteristics of the component sinusoid were selectively altered until any pairing of any two of these four forcing functions would show them to be linearly uncorrelated. The correlation coefficient relating the forcing functions was -.003.

The Visual Display

A 15.24 cm x 10.16 cm rectangular area about the centre of the scope screen was designated as the display area (see Figure 4.1b). The demarcation for the display was 2 cm wide red insulating tape strip. A bright 10.16 cm x 2 mm light green vertical line was free to move from side to side along a plane perpendicular to the subject's line of vision from the centre of the display. The greater the lateral displacement of the line from centre, the greater the magnitude of tracking error. An adjustable stem and shade lamp fitted with a 40 watt white, shadow-ban, bulb was set well above the display area facing away from the subject. The purpose of this light source was to provide background illumination, as well as to eliminate residual afterimages due to slow decay of the line on the CRT phosphor. The control display movement relationships were set to be compatible, so that moving the control to one side caused the line to move in the same direction.

The Auditory Display

The auditory display was set to represent, in movement, an auditory analog of the visual display. When a single tone is presented binaurally to the subject over stereo headphones so that the perceived loudness of the tone is the same in each ear, the combined phenomenal experience is that of a single tone centered in the middle of the head between the ears. Increasing the volume in one ear causes a phenomenal lateral shift in the perceived position of the tone from center towards that ear. By varying inversely and in proportional fashion the relative loudness of the tone in each ear, such an auditory display can therefore be used to represent both the magnitude and direction of tracking error. The greater the lateral displacement of the tone from 'center' the greater the tracking error.

A 1KHz pure tone was presented binaurally to subject's ears over stereo Koss-Pro headphones. Two four-quadrant multipliers (see Appendix C) were used to provide the auditory shift. Each multiplier fed one earpiece with a tone that was inversely related in amplitude to the tone presented over the other headpiece. The loudness of the tone therefore was constant throughout the range of movement. When the tone was presented fully to one headphone the measured volume was approximately 78 dB. As in the visual display the compatibility of the control/display movement relationships was preserved.

Setting Equivalence Between the Displays

The visual and auditory error signal displays were made analogous in other ways besides lateral left-right movement of the line and the tone. For example, an attempt was made to make the line and the tone appear to move through the same distance at the same speed. In order to establish these display relationships the following procedure was used. A single sinusoid was used to drive the tone from one ear to the other. This same sinusoid was also used to drive the line on the scope. The subjects then adjusted the gain on the oscilloscope so that the line moved at the same velocity and through a comparable distance as the tone. When the subjects were fairly certain that the adjustment made the two displays feel like they were 'equivalent', the E measured the distance travelled by the line from one reversal to the other. Several students helped in the calibration. Since the average distance was nearly six inches (15.24 cm) this is the visual display width that was used. Moreover, since the zero error auditory reference was not available to the E for inspection, in order to ensure that the true zero error value corresponded to the phenomenal 'center' of the head, the following procedure was devised: the forcing function was set to a constant value of 0 Volts. The E, using the analog computer digital voltmeter, then set the joystick output voltage to a constant 0 Volts (no integration was involved, so that the error signal presented to the subject's ears was also 0 Volts. The subject was then provided with a gain control whereby he could increase or decrease the volume of the tone presented to his right ear. With this control the subject was able to move the perceived tone from one ear to the other and thus centre it. When the subject had done so the E then wiggled the joystick from side to side (displacing the position of the tone) and then asked the subject to 'center' the tone once more but this time using the joystick instead. The _E_ could then determine the degree of correspondence between the 'middle of the head' reference and true zero error. This procedure proved most effective, with the added advantage that it compensated for individual ear asymmetries and day to day variation in hearing (due to minor colds, wax etc.). Since the zero error auditory reference was not independently marked to the subject, but rested entirely on subjective experience, the zero error visual reference was not marked on the scope. Rather subjects were told to keep the line in the centre of the display window (see Figure 4.1b). Since Vinje and Pitkin (1972) noted that visual and auditory compensatory tracking performance was equivalent only when the visual display graticule was removed,it was felt that by removing an objective visual zero error reference, tracking difficulty would be more or less the same between the tasks. Nevertheless, auditory tracking NMSE was almost always found to exceed visual tracking NMSE. Since the aim of the experiment was not directly concerned with enabling a comparison between visual and auditory tracking _per se_, no attempt was made to establish any system asymmetries ,either in the control or display characteristics. But, although tracking NMSE values differed between modalities, examination of the tracking linearity measure, R_{max}, revealed that subjects could track the auditory input as well as they could track the visual.

Procedure

Conditions, Trials and Sessions.

The twelve subjects were assigned to three groups of 4 subjects each. Each of these groups worked with a different forcing function bandwidth. The subjects in each group performed continuous compensatory tracking under six different conditions.

Each subject took part in nine 1 hour sessions. The first three of these were devoted to training the subjects, and the remaining six sessions were experimental sessions. During the training sessions the subjects were given detailed instructions concerning the first-order control dynamics, the trials, and the various tracking tasks (see Instructions: Experiment 1, Appendix D). Any questions that the subjects asked were answered at this time. In all instances, the subjects were explicitly instructed to minimize tracking error, and to weigh the tasks equally in terms of importance. No one task was assigned as 'primary'. In the first session the subjects were familiarized with the tone and line centering procedures, and were given three trials in each tracking condition, making a total of 18 trials. In the two following training sessions, six trials of each tracking condition were given. Throughout the training sessions subjects received feedback concerning tracking performance over the various trials.

The subjects were told that if performance dropped suddenly for any one single trial relative to comparable trials, he would be queried about it and the trial would have to be repeated. Subjects were told to do their best at all times.

Due to equipment limitations, it was not possible to counterbalance the handedness factor. Subjects were then arbitrarily instructed to perform visual tracking with the left hand, and auditory tracking with the right. This mode of responding was used throughout the entire experimental program.

Subjects returned for six more experimental sessions. During each of these sessions the subjects performed only one tracking condition. The order of presentation of conditions over sessions was randomized between subjects and is shown in Table 4.1

Each tracking run, or trial, lasted 71.2 secs. Data collection always began 20 secs after the start of each trial. The forcing function, the subject's output, and the system output signals in each tracking loop were digitized on-line at a rate of 10 samples per second from the analog computer trunk terminals. At the end of each trial the computer program calculated and printed the normalized mean-squared tracking error measure for each loop, and the sampled data were stored on magnetic tape for subsequent

TABLE 4.1

Tracking condition presentation order in Experiment 1

Input Bandwidth (rad/sec)	Subject	SESSION 1	2	3	4	5	6
.49	1	VICOPY	VISUAL	AUCOPY	BODIFF	AUDITO*	BOSAME
	2	AUCOPY	BOSAME	BODIFF	AUDITO	VICOPY	VISUAL
	3	BODIFF	AUDITO	VICOPY	BOSAME	VISUAL	AUCOPY
	4	AUDITO	VISUAL	BOSAME	AUCOPY	AUDITO	BODIFF
.86	1	BOSAME	AUDITO	AUCOPY	VICOPY	VISUAL	BODIFF
	2	AUCOPY	BODIFF	VISUAL	VICOPY	AUDITO	BOSAME
	3	BODIFF	VICOPY	BOSAME	VISUAL	AUCOPY	AUDITO
	4	VISUAL	BOSAME	VICOPY	AUDITO	BODIFF	AUCOPY
1.84	1	VISUAL	BOSAME	AUCOPY	VICOPY	BODIFF	AUDITO
	2	VICOPY	VISUAL	BOSAME	AUDITO	BODIFF	AUCOPY
	3	AUCOPY	AUDITO	VISUAL	BODIFF	BOSAME	VICOPY
	4	BODIFF	AUDITO	VICOPY	VISUAL	BOSAME	AUCOPY

*For the sake of ease of presentation the letters 'RY' in AUDITORY have been ommitted.

off-line analyses. In addition, the mean tracking error was also printed. This measure was not used in the data analysis but was simply used at run time to provide E with information concerning the unmarked zero error visual and auditory references used by the S. This measure indicated whether the tracking error signal oscillated normally about reference with no consistent bias in sign. Perusal of this measure revealed no such obvious biases and, therefore, no trials had to be repeated nor discarded for this reason.

At the beginning of each tracking session the subjects were given three practice trials. They were then given two blocks of twelve trials each with a five minute rest period between the blocks. Subjects were also encouraged to use the intertrial interval, which lasted approximately 30 secs, as a partial rest period. All that the subjects had to do during the intertrial interval was to keep the line or/and the tone centered in the absence of any forcing function. The beginning of each trial was then easily detected as the forcing function always began with a nonzero voltage value. The first two trials in each block were not considered in the analyses. Tracking performance during each block was regular and stable, indicating that the subjects had mastered the various tasks.

RESULTS

Analysis of Tracking NMSE Measures.

Visual Tracking

Average visual tracking NMSE values, computed over trials, for each subject individually, in each tracking condition and for the .49, .86 and 1.84 rad/sec forcing function input signal bandwidths considered are presented in Table 4.3. These data were then submitted to an analysis of variance comprising two chief factors: (1) a between subjects factor, with three levels, corresponding to the .49, .86 and 1.84 rad/sec signal bandwidths, and (2) a repeated measures tracking conditions factor, with four levels, corresponding to the VISUAL, VICOPY, BOSAME and BODIFF tracking conditions. A summary ANOVA table is presented in Table 4.4. Mean visual tracking NMSE values computed over trials and subjects, in the various visual tracking conditions are plotted as a function of visual forcing function signal bandwidth in Figure 4.3.

Examination of Table 4.4 reveals that the bandwidth main effect was significant, as was the tracking conditions main effect. The input bandwidth by tracking conditions two-way interaction was not significant. Examination of Figure 4.2 reveals a progressive overall monotonic increase in visual tracking NMSE

TABLE 4.2

Overall measures of tracking error , NMSE , tracking linearity R_{max}, and average processing delay, τ , for visual and auditory tracking inputs, and for single and dual-task conditions, averaged over tracking input bandwidth and subjects.

Input Modality	Performance Measure	SINGLE	SINGLE + COPY	BOSAME	BODIFF
			TRACKING CONDITION		
	NMSE	.081	.130 (61)	.198 (144)	.215 (165)
VISUAL	R_{max}	.983	.975 (8)	.929 (6)	.953 (3)
	τ (in msec)	264	360 (36)	481 (82)	513 (94)
	NMSE	.191	.286 (50)	.295 (54)	.383 (101)
AUDITORY	R_{max}	.960	.935 (3)	.908 (5)	.909 (5)
	τ (in msec)	451	571 (27)	434 (-4)	592 (31)

Note: Figures in brackets represent % change relative to single-task performance and attributable to the requirement to time-share tracking. Positive values represent decrements in performance due to time-sharing requirements, negative values represent improvements.

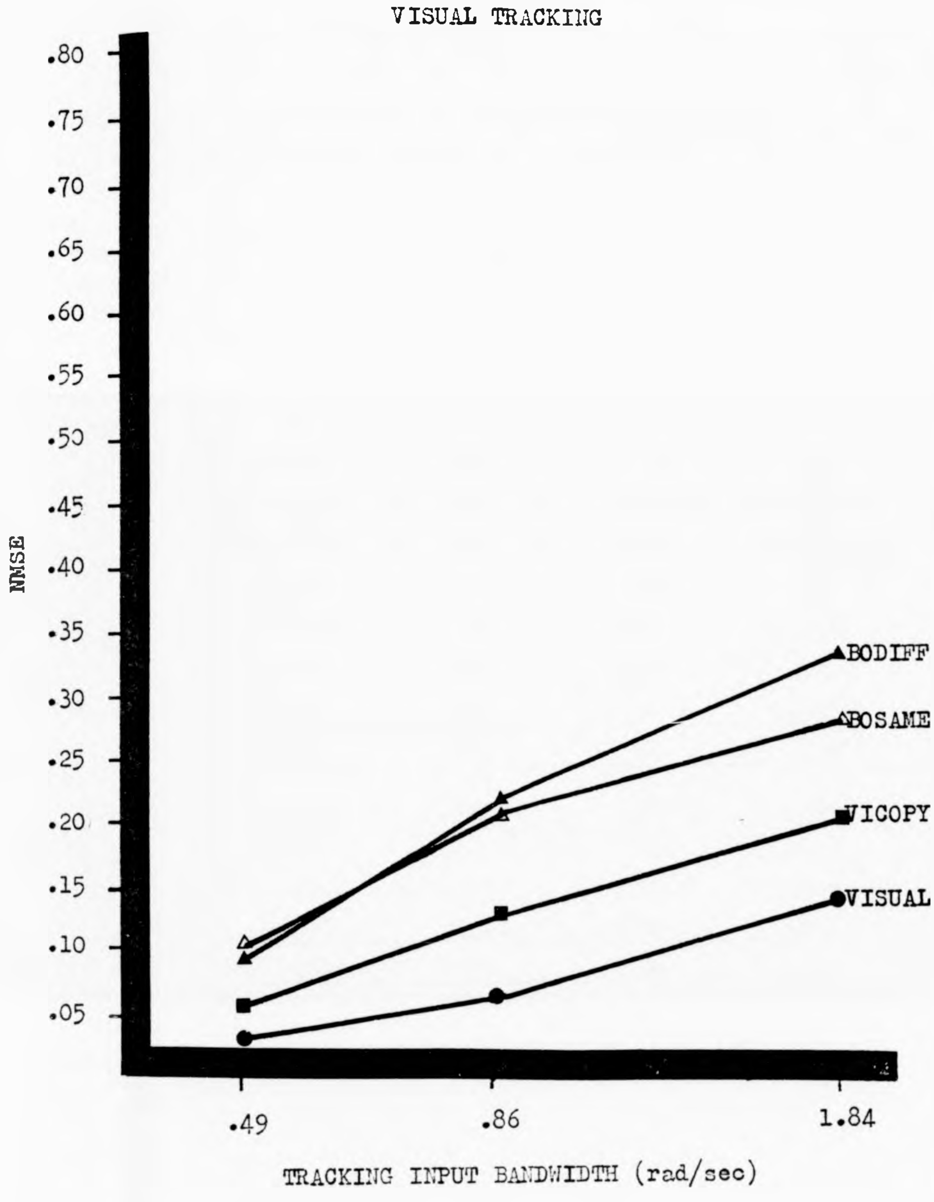

Fig. 4.2.- Normalized mean-squared tracking error in each tracking condition as a function of input bandwidth.

TABLE 4.3

Effect of input bandwidth on Normalized Mean-Squared Error in the visual tracking conditions. Experiment 1.

S	Input Bandwidth (rad/sec)	TRACKING CONDITION			
		VISUAL	VICOPY	BOSAME	BODIFF
1	.49	.035	.064	.115	.062
2		.040	.071	.132	.157
3		.036	.040	.103	.084
4		.027	.058	.066	.074
		$\bar{X}$= .035	.058	.104	.094
1	.86	.078	.172	.063	.115
2		.104	.212	.611	.416
3		.051	.077	.098	.131
4		.031	.050	.071	.210
		$\bar{X}$= .066	.128	.210	.218
1	1.84	.168	.268	.347	.484
2		.166	.227	.166	.270
3		.136	.207	.373	.326
4		.096	.119	.236	.256
		$\bar{X}$= .142	.205	.280	.334

Average of 20 trials in each subject by tracking condition cell.

TABLE 4.4

Summary ANOVA Table of average visual tracking
NMSE data. Experiment 1.

Source	DF	SS	MS	F	PROB
Subjects	11	0.448			
Bandwidth {B}	2	0.225	0.112	4.5192	0.0434
EB1	9	0.224	0.025		
Conditions {C}	3	0.140	0.047	8.2142	0.0005
{C x B}	6	0.021	0.004	0.6177	0.7159
EW1B1	27	0.153	0.006		
W	36	0.314			

TSQ/N= 1.1716 N= 48 SST= 0.7625

NOTE: In this as in all the summary ANOVA tables the following terminology applies:

EB1 = Error term between.

EW1B1 = Error term within.

W = Total within error term.

TSQ/N = Total squared divided by number of observations.

N = Number of observations.

SST = Sum of squares total.

with tracking input bandwidth. This result is consistent with numerous others in the literature (e.g., Elkind, 1956; Levison and Elkind, 1967). The result is also consistent with the notion that as the tracking input bandwidth is increased, and the information content in the signals increases, the tracking task becomes progressively more difficult. If we now turn to the individual curves representing each tracking condition, we note that tracking NMSE associated with the performance of each tracking condition also increases regularly with tracking input bandwidth. Hence, the increase in overall tracking NMSE is not tied in any obvious way to the time-sharing requirement, but is directly attributable to input signal bandwidth.

Tracking NMSE was lowest in the single-task VISUAL tracking condition, and highest in the dual-task BOSAME and BODIFF tracking conditions. Intermediate between these two extremes, we observe the NMSE values associated with the VICOPY condition, where the visual tracking task was performed in conjunction with a manual copying task. Post hoc multiple-treatment means comparisons, by Newman Keuls procedure, revealed that the contrast between average tracking NMSE in the VISUAL and VICOPY tracking conditions was not statistically significant, but those between the VISUAL and BOSAME and BODIFF conditions to be highly so ($p<.001$). The contrasts between the VICOPY and BOSAME , and VICOPY and BODIFF, tracking conditions were also statistically significant ($p<.05$). If we examine, however, the VICOPY NMSE curve we see it well elevated, and running a more or less parallel course, above that for the single-task, VISUAL, control condition. The overall relative decrement in performance caused by the addition of the copying task (see Table 4.2) may not be as great as that induced by the requirement to perform the visual and auditory tracking tasks together, but, nevertheless, may not be altogether negligible.

Although tracking NMSE was slightly lower in the BOSAME relative to that in the BODIFF tracking condition, it would appear that the subjects were dealing with the correlated signals as if they were unrelated input signals. Some support for the notion that subjects deal and extract information from otherwise identical visual and auditory inputs as if they represented distinct sources of information comes from Vinje and Pitkin's (1972) study. These researchers point out that when subjects are displayed visual tracking error also as auditory feedback, they utilize the information from both inputs instead of from only one alone. Although somewhat variable, these relationships are well respected for all the subjects taking part in the experiment. Table 4.3 shows, for all the subjects, lower NMSE values in the single-task conditions relative to those in the time-shared tracking conditions.

Auditory Tracking.

Average auditory tracking NMSE values, computed over trials, were analyzed in the same way as were those in the visual tracking conditions. Individual subject average tracking NMSE values in each tracking condition are presented in Table 4.5. Mean tracking NMSE values computed over trials and subjects are plotted as a function of forcing function signal bandwidth in Figure 4.3. Individual subjects average NMSE data in the various tracking conditions were submitted to a two-way analysis of variance.A summary ANOVA table is presented in Table 4.6.

The auditory tracking NMSE pattern of results was very similar to that observed in the visual tracking conditions. Examination of Table 4.6 reveals that both the forcing function signal bandwidth and tracking conditions main effects were highly significant. Overall auditory tracking NMSE was found to increase as the forcing function input signal bandwidth was increased from .49, to .86 and to 1.84 rad/sec. The observed NMSE values for these signal bandwidths were .109, .320, and .438 respectively. When subjects performed the AUDITORY tracking single-task control condition, the corresponding NMSE value observed was lower than that observed when subjects performed the, dual-task, AUCOPY tracking condition. These values were .191 and .286, and although the contrast between these treatment means was not statistically

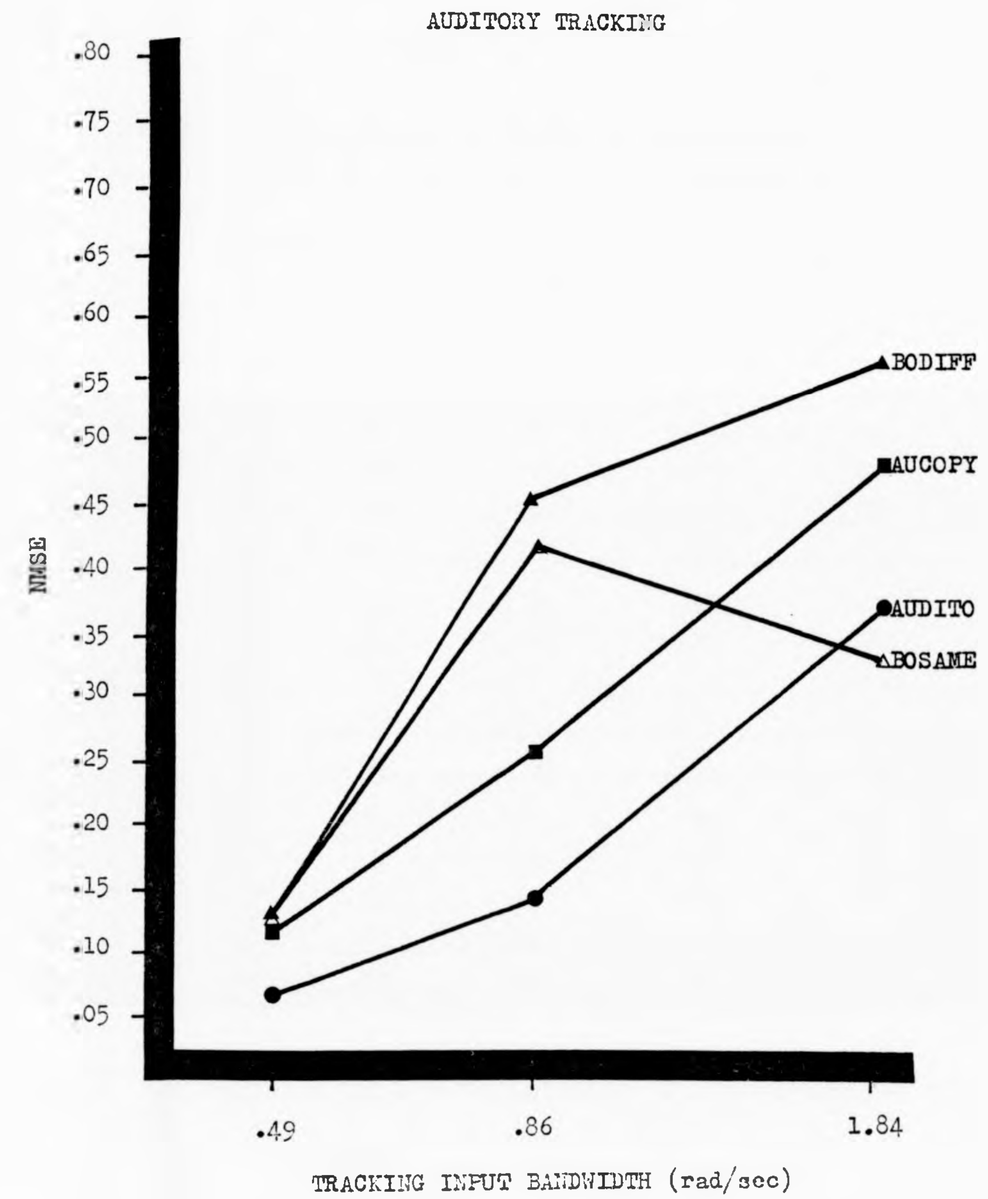

Fig. 4.3.- Normalized mean-squared tracking error in each tracking condition as a function of input bandwidth.

TABLE 4.5

Effect of input bandwidth on Normalized Mean-Squared Error in the auditory tracking conditions. Experiment 1.

S	Input Bandwidth (rad/sec)	TRACKING CONDITION AUDITORY	AUCOPY	BOSAME	BODIFF
1		.057	.098	.118	.080
2	.49	.097	.170	.166	.211
3		.051	.065	.115	.111
4		.064	.131	.104	.099
		$\bar{X}$= .067	.116	.126	.126
1		.115	.173	.193	.377
2	.86	.160	.299	.588	.466
3		.123	.161	.440	.143
4		.168	.401	.463	.844
		$\bar{X}$= .142	.259	.421	.458
1		.329	.462	.593	.982
2	1.84	.378	.479	.270	.365
3		.326	.444	.240	.324
4		.427	.546	.245	.594
		$\bar{X}$= .365	.483	.337	.566

Average of 20 trials in each subject by tracking condition cell.

TABLE 4.6

Summary Analysis of Variance Table of average auditory tracking NMSE data. Experiment 1.

Source	DF	SS	MS	F	PROB
Subjects	11	1.249			
Bandwidth {B}	2	0.889	0.444	11.1036	0.0039
EB1	9	0.360	0.040		
Conditions {C}	3	0.222	0.074	4.8588	0.0079
{C x B}	6	0.183	0.030	2.0007	0.1001
EW1B1	27	0.411	0.015		
W	36	0.815			
TSQ/N=	4.0009	N= 48		SST= 2.0642	

significant, it nevertheless represents a 50% decrement in auditory tracking performance. Significant increases in auditory tracking NMSE of 54% and 100% were found to accompany the introduction of the visual tracking task in the BOSAME ($p<.05$) and BODIFF ($p<.001$) tracking conditions.

The relative decrements in auditory tracking performance observed when subjects performed the BOSAME and AUCOPY time-shared tracking conditions were almost equivalent. The only difference between these two tracking conditions is that in the former, subjects were required to reduce tracking error simultaneously between the tracking loops because the forcing functions were identical. In the AUCOPY tracking condition subjects were also required to respond using both hands, tracking with one and copying the tracking hand movements with the other. Two possible interpretations are, therefore, tenable. One is that response interference factors were producing the BOSAME and BODIFF time-sharing decrements in performance. The other is that if subjects in carrying out the BOSAME tracking condition might have realized that the same forcing functions were disturbing the tracking loops, then it is possible that they were not tracking both forcing functions but were simply performing the VICOPY,or the AUCOPY, tracking task. In order to track the identical signals simultaneously, subjects simply had to track one of the signals, ignoring the other, and copy the movements of the tracking hand with the other hand.

There is good reason to believe, however, that subjects were not adopting a tracking/copying strategy in performing the BOSAME tracking condition. Firstly, the considerable reduction in auditory tracking NMSE which would accompany such a strategy, would most likely be distributed between subjects in all the forcing function bandwidths considered and not only in the 1.84 rad/sec signal as is evident from perusal of Figure 4.3. Secondly, if we examine Table 4.15,we readily observe that the crosscorrelation peak values relating the subject's control command signals $c_v(t)$ and $c_a(t)$ in the VICOPY and AUCOPY tracking conditions are almost equivalent, whereas they differ considerably from those in the BOSAME tracking condition. The overall peak correlation coefficient between the control command signals in the BOSAME tracking condition had a value of .616. Whereas, those for the VICOPY and AUCOPY tracking conditions were reliably higher with peak values of .934 and .943 respectively $\{F(2,8) = 122.589; p<.0001\}$. Thirdly, the average phase difference between the controlling hand output signal and that of the copying hand was in all instances less than the 100 msec crosscorrelation shift, and thus is reported in the Table as a zero τ value. The comparable phase difference values between the control command signals in the BOSAME tracking condition was relatively greater for low forcing function signal bandwidth, but then was found to decrease as the bandwidth of the signals was increased. The phase difference between the $c_v(t)$ and $c_a(t)$ signals was significantly greater in the BOSAME tracking condition than that observed in the VICOPY and AUCOPY tracking conditions { $F(2,18) = 8.780$, $p<.01$}.

The higher crosscorrelation function peak values and the notable reduction in relative phase between the $c_v(t)$ and $c_a(t)$ signals with increasing signal bandwidth in the BOSAME tracking condition, coupled with the marked decrease in auditory tracking NMSE in this condition, suggests that with increasing signal bandwidth, the subjects might have been able to note similarities between the forcing function input signals. If so, it would appear that the effect was to facilitate auditory tracking performance. In examination of Figure 4.7 we note that average auditory tracking τ in the BOSAME tracking condition is considerably less than that in the BODIFF tracking condition. Such a reduction in τ would contribute to an overall reduction in tracking NMSE, and we see in Figure 4.3 that it does. Turning to Figure 4.5, we observe, however, that auditory tracking linearity, R_{max}, in the BOSAME condition is no different from that in the BODIFF condition. The observed reduction in auditory tracking NMSE in the BOSAME condition represented in Figure 4.2, can therefore be attributed to a reduction in processing delay, τ, associated with tracking correlated inputs. But why subjects,when tracking the 1.84 rad/sec signals,would notice the correlation between the signals, and not so other subjects tracking the lower bandwidths is not clear. Finally, it should, perhaps, be noted that the control dynamics in the copying task were first order. Because first order controls are unstable,a copying strategy implemented in one of the tracking loops when performing the BOSAME tracking condition, would only be effective if the copying response signal mean and RMS values were equivalent to those of the forcing function being selectively ignored. Otherwise unchecked error would integrate over the tracking run, to the detriment of the overall performance of the tracking task.

Analysis of Tracking Linearity Measure R_{max}.

Visual Tracking

Maximum peak values R_{max} in the crosscorrelation function relating the forcing function input signal and the system output signal were averaged over trial replications, for each subject individually, in each tracking condition, and for each input bandwidth. These values are presented in tabular form in Table 4.7. These values were then submitted to a two-way analysis of variance. A summary ANOVA Table is presented in Table 4.8. Average R_{max} values for each tracking condition and tracking input

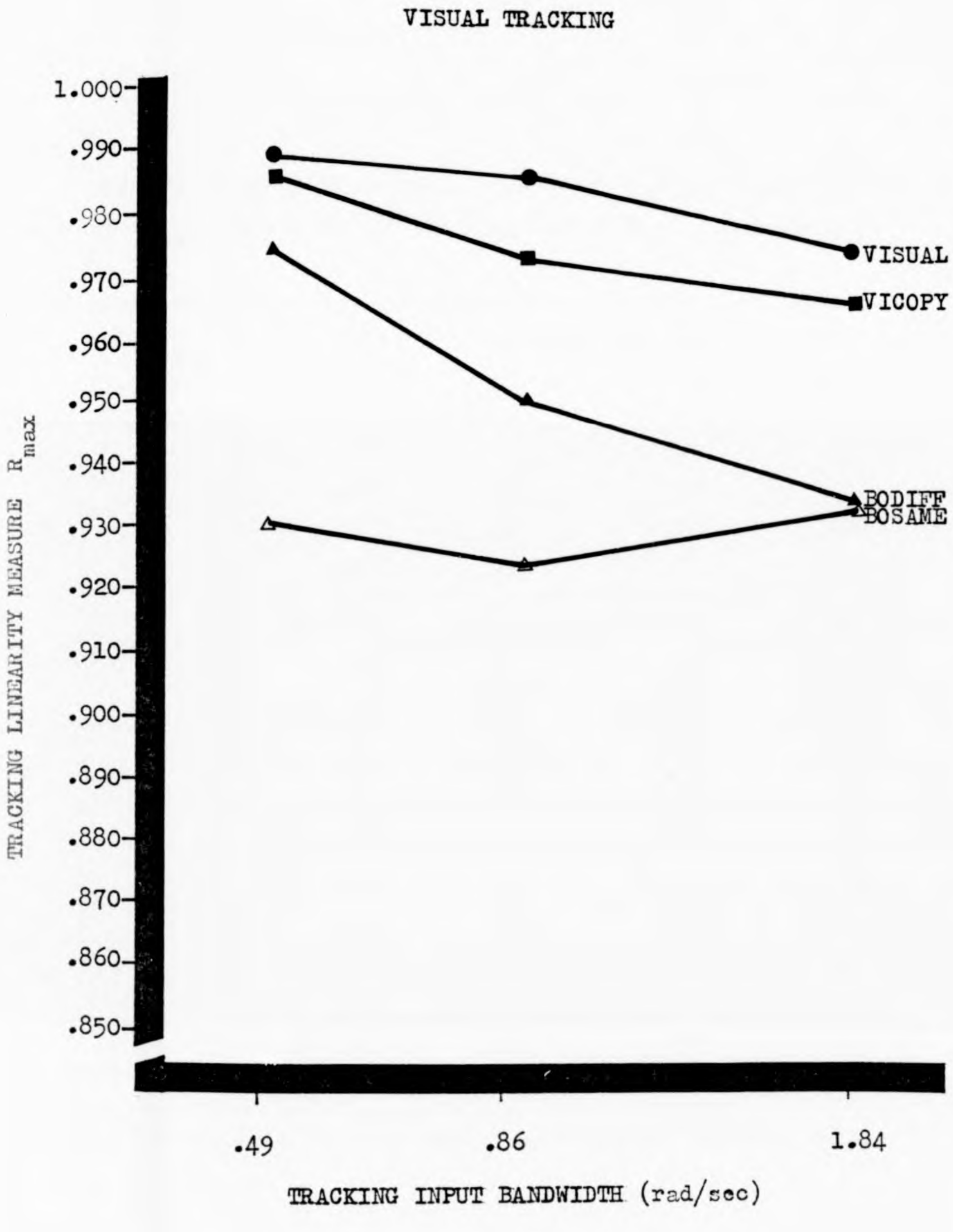

Fig.4.4.- Tracking linearity measure R_{max} as a function of input bandwidth in each tracking condition.

TABLE 4.7

Effect of input bandwidth on average tracking linearity measure, R_{max}, in the visual tracking conditions. Experiment 1.

S	Input Bandwidth (rad/sec)	TRACKING CONDITION VISUAL	VICOPY	BOSAME	BODIFF
1	.49	.990	.984	.983	.976
2		.984	.980	.772	.960
3		.989	.992	.977	.981
4		.993	.984	.987	.982
		$\bar{X}$= .989	.986	.930	.975
1	.86	.982	.953	.982	.972
2		.973	.957	.746	.889
3		.991	.989	.982	.977
4		.996	.991	.988	.963
		$\bar{X}$= .986	.973	.924	.950
1	1.84	.970	.951	.936	.886
2		.959	.959	.947	.954
3		.983	.968	.917	.947
4		.988	.987	.940	.947
		$\bar{X}$= .975	.966	.935	.934

Average of 20 trials in each subject by tracking condition cell.

TABLE 4.8

Summary Analysis of Variance Table of average visual tracking linearity, R_{max}, measures. Experiment 1.

Source	DF	SS	MS	F	PROB
Subjects	11	0.040			
Bandwidth {B}	2	0.003	0.001	0.3062	0.7464
EB1	9	0.037	0.004		
Conditions {C}	3	0.021	0.007	3.7232	0.0236
{C x B}	6	0.002	0.001	0.2143	0.9677
EW1B1	27	0.050	0.002		
W	36	0.073			
TSQ/N=	44.2522	N= 48		SST= 0.1132	

signal bandwidth, averaged over trial replications and subjects are presented graphically in Figure 4.4. Tracking linearity was not found to decrease with increases in input bandwidth from .49 to 1.84 rad/sec. Examination of Table 4.8,however, reveals that a non significant decrement in tracking linearity did occur as the forcing function bandwidth was increased, so the effect might have been significant had higher input bandwidths been considered. Tracking linearity was found, however, to vary significantly with tracking conditions. R_{max} values were highest when subjects performed the single, VISUAL, control task, and lowest when subjects performed the dual-task BOSAME condition ($p<.05$). This change represents a 6% relative decrement in tracking linearity when moving from single-task to dual-task performance. The only other significant contrast was between visual R_{max} in the VICOPY and BOSAME conditions, ($p<.05$). The requirement to time-share visual tracking with an additional response copying task did not reduce tracking linearity considerably. The effect was, however, more marked when the visual tracking task was time-shared with the auditory tracking task in the BOSAME condition. The contrast between the VISUAL and BODIFF R_{max} measures was not quite significant.

Auditory Tracking

R_{max} values in each tracking condition, for each individual subject, averaged over trial replications, and for each tracking input bandwidth are presented in Table 4.9 . These

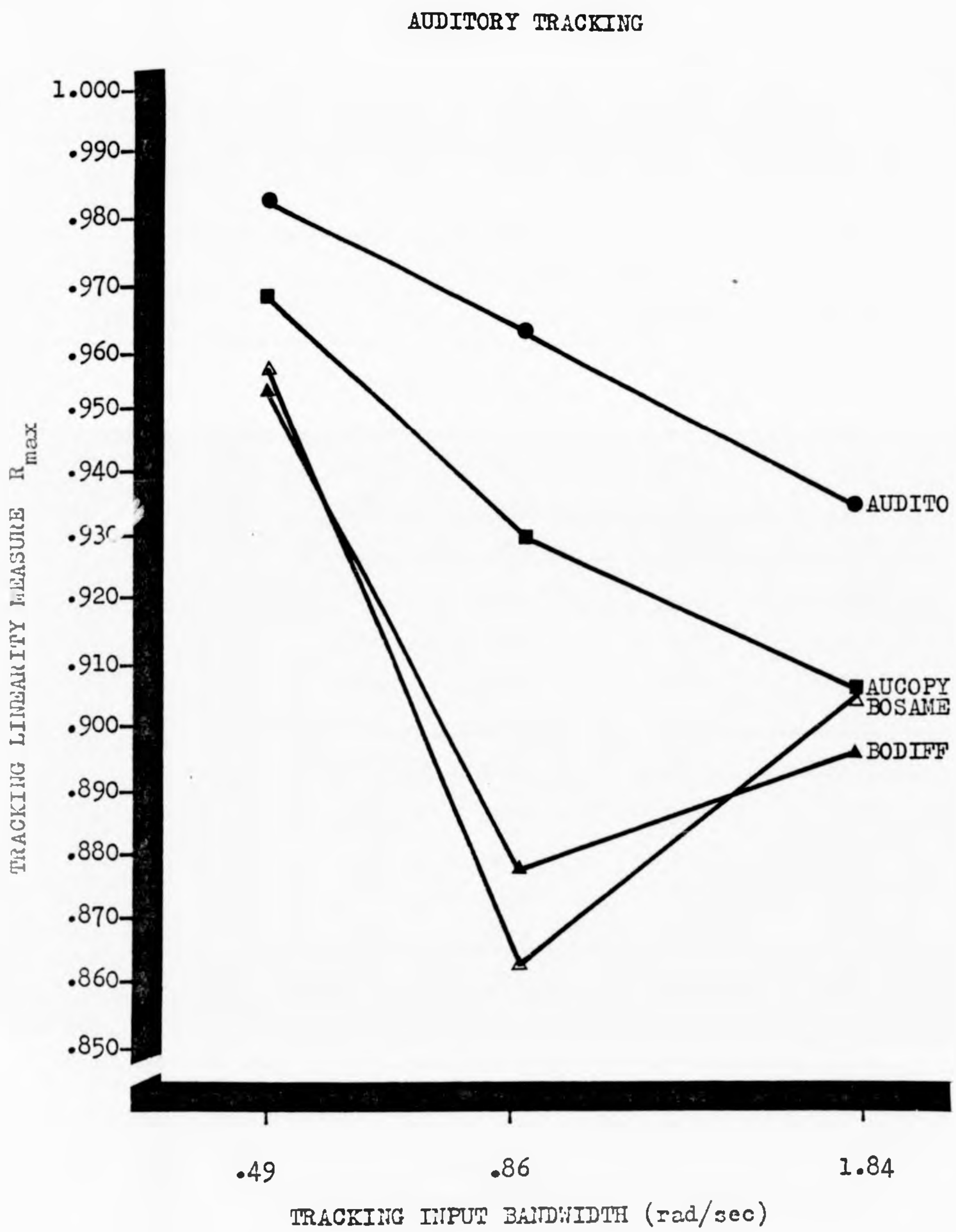

Fig. 4.5.- Tracking linearity measure R_{max} as a function of input bandwidth in each tracking condition.

TABLE 4.9

Effect of input bandwidth on average tracking linearity measure, R_{max}, in the auditory tracking conditions. Experiment 1.

S	Input Bandwidth (rad/sec)		TRACKING CONDITION		
		AUDITO	AUCOPY	BOSAME	BODIFF
1	.49	.984	.973	.946	.964
2		.974	.949	.956	.927
3		.986	.967	.958	.958
4		.985	.979	.963	.965
		$\bar{X}$= .982	.967	.956	.953
1	.86	.972	.957	.944	.909
2		.966	.920	.853	.891
3		.972	.944	.937	.954
4		.940	.899	.718	.758
		$\bar{X}$= .963	.930	.863	.878
1	1.84	.953	.917	.803	.858
2		.938	.905	.949	.933
3		.944	.930	.931	.936
4		.910	.877	.940	.862
		$\bar{X}$= .936	.907	.906	.897

Average of 20 trials in each subject by tracking condition cell.

TABLE 4.10

Summary analysis of Variance Table of average auditory tracking linearity, R_{max}, measures. Experiment 1.

Source	DF	SS	MS	F	PROB
Subjects	11	0.079			
Bandwidth {B}	2	0.032	0.016	3.0329	0.0975
EB1	9	0.047	0.005		
Conditions {C}	3	0.022	0.007	5.8129	0.0034
{C x B}	6	0.009	0.002	1.2191	0.3271
EW1B1	27	0.034	0.001		
W	36	0.065			
TSQ/N=	41.3554	N=	48	SST=	0.1442

TABLE 4.10

Summary analysis of Variance Table of average auditory tracking linearity, R_{max}, measures. Experiment 1.

Source	DF	SS	MS	F	PROB
Subjects	11	0.079			
Bandwidth {B}	2	0.032	0.016	3.0329	0.0975
EB1	9	0.047	0.005		
Conditions {C}	3	0.022	0.007	5.8129	0.0034
{C x B}	6	0.009	0.002	1.2191	0.3271
EW1B1	27	0.034	0.001		
W	36	0.065			
TSQ/N=	41.3554	N=	48	SST=	0.1442

values were submitted to analysis of variance. A summary ANOVA Table is presented in Table 4.10. R_{max} values averaged over trials and subjects in each tracking condition are plotted as a function of tracking input bandwidth in Figure 4.5.

Auditory tracking linearity was not found to decrease significantly with tracking input bandwidth, but there was a hint of a reduction (see Table 4.9). Again, the low signal bandwidths used are suspect. Auditory tracking linearity was found to vary significantly with tracking condition manipulations. Examination of Table 4.2 reveals that the subjects were able to track the input signals more accurately when they only had the auditory tracking task to perform, than when they had to time-share it with the visual tracking task ($p<.001$). When the copying task was added, auditory tracking R_{max} was reduced from .960 to .935, a 3% drop in tracking linearity, but the contrast was not statistically significant. Examination of Table 4.9 reveals this trend to be well represented in the .49 and .86 rad/sec group of subjects, and somewhat less evident in the 1.84 rad/sec group of subjects.

Closer examination of Table 4.2 reveals that overall tracking linearity measures for the VISUAL and AUDITORY tracking conditions are almost equivalent. This result indicates that the subjects could track the auditory display almost as accurately as the visual. However, when the tracking NMSE measures are also examined, the discrepancy in NMSE between the VISUAL and AUDITORY conditions is considerably greater. Such relative differences in tracking NMSE between the VISUAL and AUDITORY tracking conditions may stem from differential response delays to the visual and auditory displays. τ measures also presented for these conditions in Table 4.2 indicate that indeed, overall response delays to the auditory display were considerably greater than those to the visual display. Hence, it would appear that subjects tried to maintain high levels of auditory tracking linearity incurring both an increase in response delay, and a corresponding increase in tracking error. Subjects were perhaps doing this to keep error due to increases in tracking remnant amplitude to a minimum.

Analysis of Average Processing Delay τ Measure.

Visual Tracking

Average response delay, τ, measures were averaged over trial replications for each tracking condition, and for each subject separately. These mean values were submitted to a two-way analysis of variance, with a tracking input bandwidth between-subjects factor, and a repeated measures tracking condition factor. These τ values are presented in Table 4.11. The summary ANOVA Table is presented in Table 4.12. Average τ values computed over trials and subjects are also plotted as a function of tracking input bandwidth in Figure 4.6.

Examination of Table 4.12 reveals that average visual tracking τ values did not vary significantly as the forcing function signal bandwidth was raised from .49,to .86, to 1.84 rad/sec. The tracking conditions main effect, on the other hand, was highly significant. Examination of Table 4.2, reveals average τ in the single-task VISUAL condition to be some 100 msec lower than those in the dual-task VICOPY condition. This difference, however, is not statistically significant. Highly significant ($p<.001$) increases in τ were observed, however, when subjects performed the visual and auditory tracking tasks concurrently. A 217 msec increase was found to accompany the addition of the auditory tracking task in the BOSAME condition, and a corresponding 249 msec increase when performing the BODIFF tracking condition. Thus the concurrent performance of a visual and an auditory tracking task produced a considerable increase in average processing delay in the visual tracking task relative to that observed when the visual tracking task was performed singly. Response interference effects could only account for a 96 msec relative increase in τ between the VICOPY and VISUAL tracking conditions. Whereas, a 217 msec relative increase in τ was noted when the subjects performed the BOSAME condition. Relative to the VISUAL condition, τ was found to increase by 299 msec when the BODIFF tracking condition was

VISUAL TRACKING

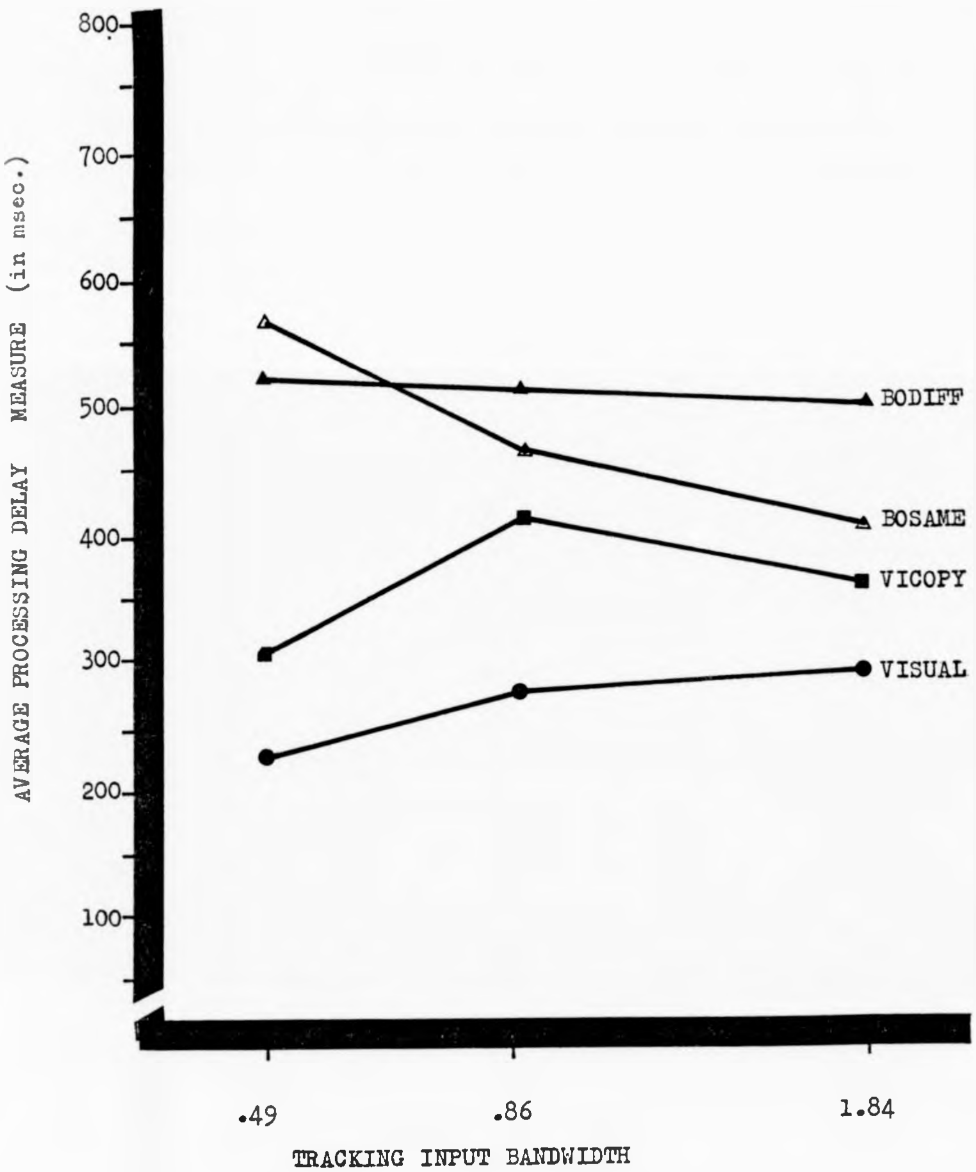

Fig.4.6.- Average processing delay measure in each tracking condition as a function of input bandwidth.

TABLE 4.11

Effect of input bandwidth on average tracking response delay measure, τ (in msec), in the visual tracking conditions. Experiment 1.

S	Input Bandwidth (rad/sec)	TRACKING CONDITION VISUAL	VICOPY	BOSAME	BODIFF
1	.49	200	220	256	350
2		230	410	1013	845
3		260	320	500	478
4		210	270	490	423
		$\bar{X}$= 225	305	565	522
1	.86	300	422	250	300
2		300	579	900	700
3		299	386	421	450
4		201	261	300	600
		$\bar{X}$= 275	412	468	513
1	1.84	320	400	520	650
2		250	350	250	380
3		320	400	500	540
4		280	310	370	440
		$\bar{X}$= 293	365	410	503

Average of 20 trials in each subject by tracking condition cell.

TABLE 4.12

Summary Analysis of Variance Table of average visual tracking response delay τ measures. Experiment 1

Source	DF	SS	MS	F	PROB
Subjects	11	610902.500			
Bandwidth {B}	2	4728.500	2364.250	0.0351	0.9661
EB1	9	606174.000	67352.664		
Conditions {C}	3	470564.500	156854.828	11.0934	0.0001
{C x B}	6	77947.500	12991.250	0.9188	0.5023
EW1B1	27	381766.000	14139.481		
W	36	930278.000			

TSQ/N= 7860245.5000 N = 48 SST = 1541180.5000 performed. If the subtractive method, in relative terms (Sternberg, 1969a,b), applies to τ as well as to RT we may note therefore: (1) response interference, attributable to the copying task, would account for an approximate 96 msec increase in τ when performing the BOSAME tracking condition. The remaining 121 msec increase could be attributable to more central attentional factors. Similarly, a 96 msec increase in τ may well have been attributable to response interferences; leaving an unexplained 153 msec increase in processing delay.

Auditory Tracking

The auditory tracking results were less straightforward. With the exception of a reduction, when the auditory tracking task was performed in the BOSAME tracking condition, τ was found to increase significantly with the introduction of additional tasks.

Mean τ measures were computed over trial replications, for each subject individually, in each tracking condition, and submitted to analysis of variance. The design used, identical in every respect to that used in the visual tracking conditions was a two-factor mixed design with repeated measures on the tracking conditions' factor, and a between subjects factor relating to input bandwidth. The summary ANOVA Table is given in Table 4.14. Mean τ values for each tracking condition and individual subjects are presented in Table 4.13. Mean τ values averaged over trials and subjects, in each tracking condition, are plotted as a function of tracking input bandwidth in Figure 4.7.

The results of analysis of variance revealed no significant consistent variation in τ with increasing tracking input bandwidth. The tracking conditions main effect was highly significant, however. The two-way input bandwidth by tracking condition interaction was not quite statistically significant. Examination of Table 4.13, for example, reveals considerably less consistent increases in τ with tracking condition, between subjects, than was initially observed for the visual tracking conditions. Figure 4.7 shows regular changes in τ with input bandwidth in the AUDITORY and AUCOPY tracking conditions, whereas τ values for the BOSAME tracking condition are some 155 msec less than those in the BODIFF tracking condition. There is no obvious explanation for the finding that auditory τ values in the BOSAME tracking condition reduce relative to those in BODIFF, other than that correlated inputs somehow facilitate the performance of the auditory tracking task sufficiently to reduce average response, or processing delay. Nevertheless, disregarding the BOSAME tracking condition τ results, for a moment, we observe the following pattern of results. Turning to Table 4.2, we note a significant increase in τ ($p<.05$) when the additional copying task is introduced. Mean τ is some 120 msec

AUDITORY TRACKING

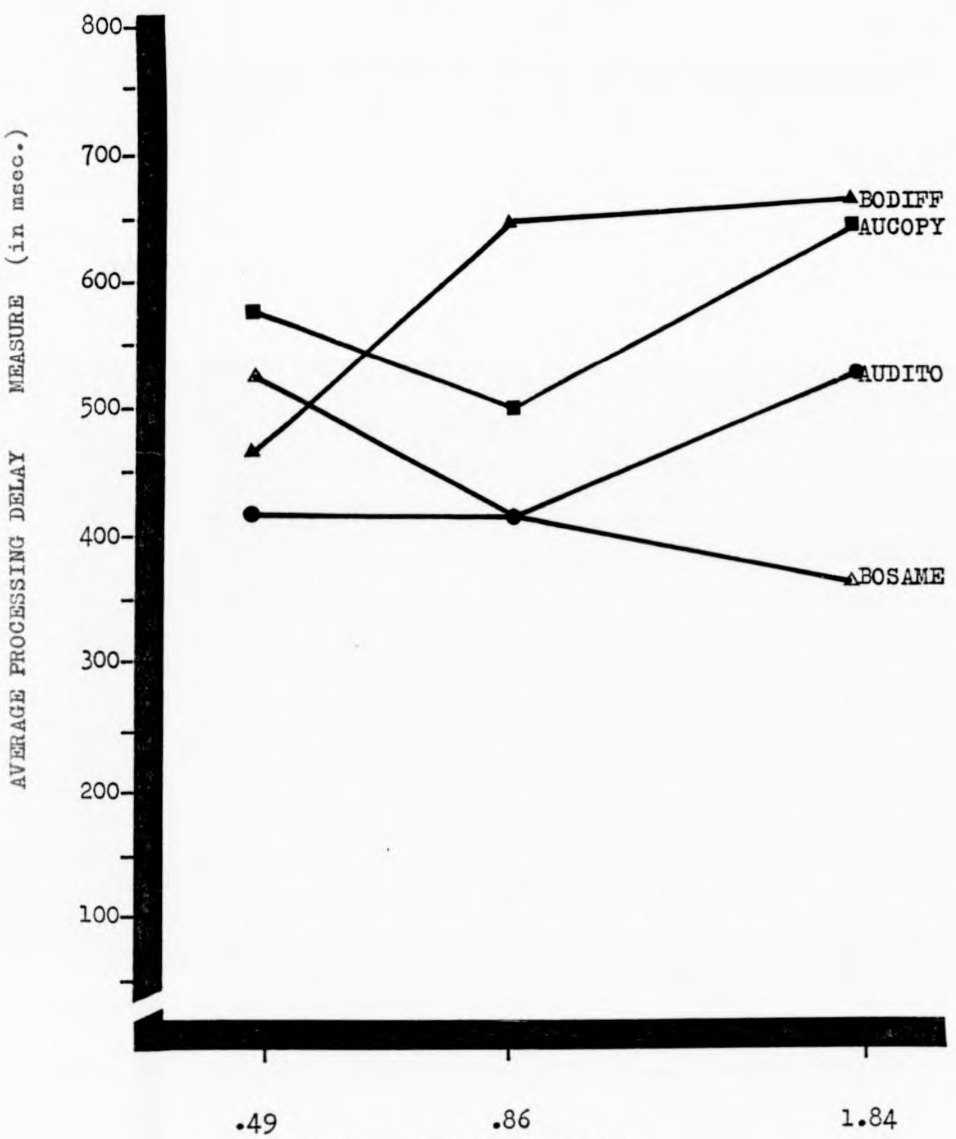

Fig. 4.7.- Average processing delay measure in each tracking condition as a function of input bandwidth.

TABLE 4.13

Effect of input bandwidth on average tracking response delay measure, τ (in msec), in the auditory tracking conditions. Experiment 1.

S	Input Bandwidth (rad/sec)	TRACKING CONDITION AUDITO	AUCOPY	BOSAME	BODIFF
1	.49	400	608	434	505
2		550	707	756	555
3		350	435	380	413
4		350	536	530	373
		$\bar{X}$= 413	572	525	462
1	.86	450	467	450	650
2		500	531	700	750
3		261	275	200	300
4		450	722	300	900
		$\bar{X}$= 415	499	412	650
1	1.84	524	640	520	1100
2		540	580	260	500
3		460	650	360	460
4		580	700	320	600
		$\bar{X}$= 526	642	365	665

Average of 20 trials in each subject by tracking condition cell.

TABLE 4.14

Summary Analysis of Variance Table of average auditory tracking response delay, τ, measures. Experiment 1.

Source	DF	SS	MS	F	PROB
Subjects	11	623275.000			
Bandwidth {B}	2	33768.000	16884.000	0.2578	0.7803
EB1	9	589507.000	65500.777		
Conditions {C}	3	235756.000	78585.336	5.7779	0.0036
{C x B}	6	198013,000	33002,168	2.4264	0.0523
EW1B1	27	367229.000	13601.074		
W	36	800998.000			

TSQ/N= 12589057.0000 N = 48 SST = 1424273.0000 longer when the subjects time-share auditory tracking in the AUCOPY condition relating to the single-task auditory tracking condition. This in turn represents a 27% relative increase in τ. Switching from Table 4.9 to Table 4.13 and comparing the two AUCOPY data columns we readily note the possibility of a tradeoff between copying accuracy and auditory tracking response delay in only one subject that is, if the subjects were to concentrate more on the copying task than on the tracking task such an asymmetry in task priority could underlie the increase in the auditory tracking task τ. This is not a consistent observation over the other subjects, however, and thus the significant increase in τ in the AUCOPY time-shared tracking condition, relative to the single-task condition, cannot be entirely explained in such terms. The additional visual tracking task in the BODIFF tracking condition, increased τ very significantly ($p<.01$) by some 141 msec overall. This represents a relative increase in τ of 31% which given the low input bandwidth involved may not be deemed negligible in its contribution to increased tracking NMSE in this condition. In partial contrast, the reduced τ values in the 1.84 rad/sec input signal, indicated in Table 4.13, may underlie the observed reduction in tracking NMSE in the BOSAME condition. This reduction in τ is represented graphically in Figure 4.7. Referring back to Table 4.2 we note, therefore, an increase in τ with the requirement to time-share auditory tracking, in all but the BOSAME tracking condition, where in effect a negligible relative reduction was observed.

TABLE 4.15

Average correlation values, R_{max}, and average response delay, τ, between the operator's output signals $c_v(t)$ and $c_a(t)$ in the BOSAME, VICOPY, and AUCOPY tracking condition for each tracking input bandwidth.

S	Input Bandwidth (rad/sec)	TRACKING CONDITION					
		BOSAME		VICOPY		AUCOPY	
		R	τ	R	τ	R	τ
1	.49	.576	250	.966	0	.923	0
2		.450	175	.965	0	.954	0
3		.543	590	.938	0	.948	0
4		.716	150	.855	0	.944	0
		$\bar{X}$= .571	292	.931	0	.943	0
1	.86	.570	200	.915	0	.950	0
2		.432	0	.930	0	.935	0
3		.600	70	.930	0	.938	0
4		.590	100	.944	0	.960	0
		$\bar{X}$= .548	93	.930	0	.945	0
1	1.84	.629	0	.916	0	.939	0
2		.782	0	.948	0	.955	0
3		.762	40	.957	0	.971	0
4		.742	0	.947	0	.902	0
		$\bar{X}$= .729	10	.942	0	.942	0

Average of 20 trials in each subject by tracking condition cell.
τ measure values are in milliseconds.

Correlation Between the Absolute Tracking Error Signals.

Average correlation coefficients, computed over trials, and standard deviation values for the BOSAME and BODIFF tracking conditions are presented for the .49, .86, and 1.84 rad/sec forcing function signals in Table 4.16. Examination of trial data as well as average correlation revealed no significantly consistent trends in the correlation values associated with the requirement to divide attention in the BOSAME and BODIFF tracking conditions. Not only were these values low, but they were as likely to be positive as negative in sign. Given that 512 sampled data pairs were involved in the computation of each correlation coefficient, r, a value exceeding the critical range ±.087 would have been significant at the .05 level of confidence. None of the values in Table 4.16 was statistically significant.

There was no evidence of a predominance of negative correlation coefficients in the .86 and 1.84 rad/sec signal bandwidths, as would have been expected, given the increased rates of incoming task-related information, if the subjects performed the tracking tasks in serial alternation. It cannot be simply argued that the visual and auditory tasks when carried out together were not sufficiently demanding of attentional resources. Consider Tables 4.3 and 4.5. Relative to single task performance, we note

TABLE 4.16

Average correlation, r, and standard deviation, σ, values between the absolute tracking error signals, $e_v(t)$ and $e_a(t)$ in each BOSAME and BODIFF tracking condition, and for each tracking input bandwidth.

S	Input Bandwidth (rad/sec)	BOSAME r	BOSAME σ	BODIFF r	BODIFF σ
1	.49	.02	.15	.01	.08
2		-.02	.17	-.02	.12
3		.05	.15	.03	.10
4		.04	.17	.03	.13
	$\bar{X}=$	.02	.16	.01	.11
1	.86	.08	.12	.08	.03
2		.06	.15	.01	.15
3		.05	.15	.02	.13
4		.08	.17	.03	.12
	$\bar{X}=$	.07	.15	.04	.11
1	1.84	.08	.18	.02	.07
2		.09	.17	-.01	.06
3		.18	.14	.09	.10
4		-.06	-.09	.05	.10
	$\bar{X}=$	.07	.15	.04	.08

Average of 20 trials in each subject by tracking condition cell.

TABLE 4.16

Average correlation, r, and standard deviation, σ, values between the absolute tracking error signals, $e_v(t)$ and $e_a(t)$ in each BOSAME and BODIFF tracking condition, and for each tracking input bandwidth.

S	Input Bandwidth (rad/sec)	BOSAME r	BOSAME σ	BODIFF r	BODIFF σ
1	.49	.02	.15	.01	.08
2		-.02	.17	-.02	.12
3		.05	.15	.03	.10
4		.04	.17	.03	.13
	$\bar{X}=$	.02	.16	.01	.11
1	.86	.08	.12	.08	.03
2		.06	.15	.01	.15
3		.05	.15	.02	.13
4		.08	.17	.03	.12
	$\bar{X}=$	.07	.15	.04	.11
1	1.84	.08	.18	.02	.07
2		.09	.17	-.01	.06
3		.18	.14	.09	.10
4		-.06	-.09	.05	.10
	$\bar{X}=$	.07	.15	.04	.08

...rage of 20 trials in each subject by tracking condition cell.

relative decrements in tracking performance, for the 1.84 rad/sec forcing functions, of 2.1 times for the BOSAME and BODIFF tracking conditions combined when visual tracking was involved, and a corresponding decrement of performance of 3.6 times when tracking was auditory.

The identical forcing functions did not increase the occurrence of high negative values of r. Nor were these values consistently different from those in the BODIFF tracking condition ($t=1.23$; $df=22$, n.s.). Assuming no curvilinearity, between the absolute tracking error signals, it would appear therefore, that when human subjects control a first order multiple single-loop compensatory tracking system, with separate presentation of single-loop tracking error to the visual and auditory modalities simultaneously, error reducing activity between the loops is not carried out, serially, on a moment to moment basis.

DISCUSSION

The requirement to time-share tracking between the visual and auditory sensory modalities in the BOSAME and BODIFF tracking conditions, has been found to produce a general decrease in tracking performance. Such a decrease in tracking performance was exhibited as a marked increase in tracking NMSE error.

Component analyses of tracking error reveal this increase to be attributable largely to an increase in average response delay, τ, and to a general reduction in tracking linearity R_{max}. The observed reduction in, R_{max}, implies, in turn, the inclusion in subject's response of commands not linearly correlated with the tracking input. Only when the forcing functions were identical, as in the BOSAME tracking condition, and only in the auditory tracking conditions was this general pattern of results violated (see Table 4.2 for an overview). Since the subject did not view the forcing functions directly, and furthermore, since analysis of the correspondence between subject's manual response signals, $c_a(t)$ and $c_v(t)$, indicates that no obvious track/copy strategies were present, it is conceivable that the subjects in the BOSAME tracking condition, in order to maintain tracking error to a minimum were adjusting their auditory tracking response delay accordingly. This adjustment in τ may have been beneficial in enabling some subjects to track the forcing function signal more accurately. Some partial support for this notion is obtained if one observes in Tables 4. 9 and 4.13 that for the 1.84 rad/sec input signal, subjects whose tracking linearity is high, i.e. subjects 2 and 4, display the lowest τ values. Whereas those whose R_{max} measures are low are also slower in responding. The combined effect of a reduction in τ, and an increase in R_{max}, would serve to reduce tracking NMSE in this condition. Since different groups of subjects tracked the

.49, .86 and 1.84 rad/sec forcing function signals (a between subjects treatment design was used in order to eliminate undesirable carry over effects (see Poulton, 1974 for a discussion), such a relationship between NMSE, R_{max}, and τ cannot readily be extrapolated to other subjects in the .49 and .86 rad/sec input bandwidths. Although, in general, in both visual and auditory tracking conditions, an increase in NMSE, a decrease in R_{max}, and an increase in τ was found to accompany the requirement to time-share tracking with a manual copying task, the decrement in task performance observed was not, overall, statistically significant. One exception to this general pattern of results was revealed, however, in the auditory tracking condition. But only a significant increase in τ was observed in the AUCOPY tracking condition. The requirement to time-share performance between the visual and auditory tracking tasks did generally show these time-sharing effects to be highly and reliably consistent, the only exception being the BOSAME auditory tracking condition discussed above.

Response interference time-sharing effects associated with the performance of the VICOPY and AUCOPY conditions could only account respectively for approximately one third and one half of the intertask interference observed when the visual and auditory tracking tasks were performed concurrently (see Table 4.2). Clearly, it is unlikely that all of the observed time-sharing decrements of task performance were due to uncontrolled response interference factors. Although auditory tracking NMSE was considerably greater than visual tracking NMSE ($p<.01$), in terms of tracking linearity estimates, R_{max}, it would appear that comparable amounts of information were being transmitted from either display. Moreover, the pattern of results obtained for the visual modality was very much like that observed for the auditory, the only discrepancy being the performance of the auditory tracking task in the BOSAME condition. Response interference may not be considered negligible, and indeed it is evidently a major contributor to the observed time-sharing decrements of task performance, but not apparently the only factor. Peripheral input interference can be discounted as a major factor underlying the observed time-shared tracking performance decrements, since task related information was presented separately to the visual and auditory sensory modalities. Whatever was inducing increases in both tracking NMSE and τ, and reducing R_{max} in the time-shared BOSAME and BODIFF tracking conditions seemed to be a rather more central information processing limitation that may be associated with genuine attentional limitations.

Increases in average tracking response delay τ measures with time-sharing requirements are consistent with single-input, serial, information processing models of attention. There was no evidence, however, of any linear functional relationship between the observed magnitude of tracking error between the loops. When tracking the visual and auditory inputs concurrently, subjects appear to be able to perform both tracking tasks simultaneously, reducing perceived tracking error from each tracking loop quite independently of their relative magnitudes. Accordingly, when subjects reduced perceived tracking error in one loop, such information processing activity did not simultaneously inhibit the simultaneous processing of tracking error information in the other tracking loop.

Yet, time-shared tracking decrements of performance associated with increases in τ need not necessarily imply either serial, single input or response, information processing. If, when subjects perform a tracking task singly, free attentional resources may be allocated to estimating, at least locally, the future course of the track (such an optimal adaptation is discussed on Page56), and the subjects may then be able to organize their response an appreciable time in advance, measured τ may be less than that observed in a dual-task condition. Hence, parallel information processing of task related information may not be denied. Increases in τ accompanying time-shared tracking could simply indicate that rather than to risk responding incorrectly, thus adding to remnant amplitude and to tracking error, the subjects may adopt a somewhat more conservative strategy and wait rather for a definitive increase in perceived tracking error before responding to it. Such a perfectly legitimate and optimal strategy does not deny the subject his parallel information processing skills. On the contrary, it could serve to relieve him, or her, from adopting a perhaps less optimal and even equally time consuming strategy involving serial attention switching between the tracking loops. This is not to deny the phenomenal experience of attention switching between these bimodal continuous information processing tasks. Indeed, the phenomenal experience when performing the visual and auditory tracking tasks concurrently was that of occasional and aperiodic focusing of attention on one task, followed by the inevitable phenomenal experience of a switch in attention when the other task is accommodated. Most controllers of the bimodal multiple single-loop system reported this tendency (including Dr. Allan Allport ho attempted the dual tasks on a visit to the Department of sychology of the University of Stirling). Yet, the phenomenal xperience of attention switching was never as rapid as once per alf second, which would be the minimum sampling rate that would nable interpolative knowledge of the incoming error signals (This ould have to be the case in order to satisfy the Sampling Theorem, ince the highest cutoff frequency was 1.84 rad/sec). Rather, the phenomenal rate of attention switching was considerably slower and seemed to be tied only superficially to significant changes in the error signals. In performing both tracking tasks simultaneously, it was often a better strategem to attend to both signals, in parallel, by monitoring from an 'external' position somewhere between the scope and one's head, than by concentrating briefly on one task and not the other. Moreover, the absence of significant negative correlation between the absolute tracking error signals in each tracking loop, is not consistent with the notion that the subjects were only capable of reducing tracking error in one task at a time. Rather, the low correlation coefficients observed indicate no functional, consistent, linear relationship between the subject's error reducing activities in each tracking loop.

CHAPTER 5.

5.1 - Experiment 2: Effect of Order of Controlled Element Dynamics

The objectives and aims of the experiment were in many respects similar to those of Experiment 1. In this experiment, however, order of control dynamics was the variant. Subjects performed visual and auditory tracking, with the same display configurations used in the previous experiment, singly and in dual-task combination. Subjects performed the VISUAL, AUDITORY, VICOPY, AUCOPY, BOSAME and BODIFF tracking conditions with zero, first and second order control dynamics.

METHOD

Subjects

Four subjects took part in this experiment. All subjects were right-handed, male, and reported normal vision and hearing. Subjects ranged in age from 16 to 27 years of age. They were all paid £0.60/hr., and as in Experiment 1 they were told that the subject with the lowest overall tracking error would receive a £2.00 bonus at the end of the experiment.

Apparatus and Materials:

The equipment used was the same as that in Experiment 1. The control dynamics, however, were changed to zero order in the first part of the experiment, raised to first order in the second, and raised once more to second order in the third part. Raising the control dynamics from proportional, to rate, and acceleration was achieved by successive integration of the joystick output signal by means of pure integrator units available in the analog computer. Analog computer program circuits are available for inspection in Appendix B. First order control dynamics were obtained by a single integration of the control output signals $m_v(t)$ and $m_a(t)$. Second order control dynamics were obtained by double, cascaded, integration of these continuous signals. The integrators were locked by diode circuits to a voltage range of $\pm 10V$, integration was at a rate of 1 Volt/sec. The forcing functions used were the .86 rad/sec. signals used in Experiment 1.

Procedure:

The experiment was divided into three distinct phases. Subjects returned to take part in all of them. During the first, subjects tracked with proportional, during the second with rate and during the third with acceleration control dynamics. This sequential raising of the control dynamics of the system was carried out in order to minimise asymmetric transfer effects (Poulton, 1974).

The subjects took part in fifteen 1-hr. daily sessions, separated only by weekends. The first part of the experiment comprised five sessions, the second four, and the third six. The subjects came for an initial "acquaintance" session during which they were introduced to the various tasks, displays, control dynamics and tracking performance criteria. During this session, subjects were familiarised with the tone centering procedure and were introduced to the tracking tasks. In order to acquaint subjects with the tracking task, and controls, and to give them an idea of what criteria constituted good tracking performance, the following procedure was followed: The subject was first given explicit instructions (see Appendix D) and then was introduced to the visual tracking task with zero order controls. The E then monitored the tracking error signal and called out to the subject when tracking error was considerable. To a given increase in tracking error the E on occasion would say something like "Oops, bring it back to zero", then "That is right, good"; and then again if the subject happened to overshoot his controlling movement, "Oops, too much, bring it back". When it was evident that the subject was getting used to tracking, the subject was then given a ten minute continuous tracking run simulating actual data gathering trials. At the end of this period the procedure was repeated for the auditory tracking task. The subjects returned for two more practice sessions during which seven trials were given in each tracking condition. At the end of the practice sessions, the subject then returned for two more ,experimental ,sessions. The subjects performed three of the six tracking conditions on the first day, and the other three on the second. The order of presentation of conditions was random, and the BOSAME and BODIFF tracking trials mixed and presented at random between the two days. Each trial lasted 71.2 secs.; data collection began, however, 20 secs. after the beginning of the trial and lasted until the end of the trial. Subjects were usually given 10 trials in each condition but performance would usually become stable after the third or fourth trial. When it seemed as if the subject was well into the task, data from six trials were then recorded and stored on magnetic tape for off-line analyses. The forcing function signals, the system output signals and the subject's command control signals were sampled once every 100 msec by the digital computer. The experimental sessions were always conducted on consecutive days. Subjects were usually run at the same hour every day between the hours of 9.00 a.m. and 1.00 p.m., and were allowed to exchange hours between themselves.

These times and adjustments were maintained throughout the entire experimental program. After the experimental sessions were over subjects returned for two more practice and two more experimental sessions, but this time to track using first order controls. After this part of the experiment was completed the control dynamics were raised to second order. The subjects found second order control most difficult, especially in the auditory tracking conditions. Auditory tracking performance was in fact so poor that E appealed to the subjects' generosity and was able to extend the practice period to four consecutive days. Two experimental sessions identical in every respect to those for lower control orders were then conducted.

RESULTS

Analysis of Tracking NMSE Data

Visual Tracking

Average NMSE, computed over trials, for each subject individually, in each tracking condition and for the three controlled element dynamics investigated are presented in tabular form in Table 5.2. Individual subject data were submitted to an analysis of variance comprising two chief repeated measures factors: (1) control dynamics, with three

TABLE 5.1

Overall measures of visual and auditory tracking NMSE, tracking linearity, R_{max} and average tracking response delay, τ, in the single-task and dual-task conditions, and for zero, first, and second order controlled element dynamics. Experiment 2.

INPUT	CONTROL ORDER	MEASURE	SINGLE	SINGLE + COPY	BOSAME	BODIFF
				TRACKING CONDITION		
VISUAL	ZERO	NMSE	.034	.080	.119	.155
		R_{max}	.980	.986	.963	.969
		τ (in msec)	307	316	385	388
	FIRST	NMSE	.049	.067	.120	.154
		R_{max}	.982	.984	.982	.970
		τ (in msec)	319	376	507	475
	SECOND	NMSE	.336	.373	.574	.659
		R_{max}	.911	.866	.850	.807
		τ (in msec)	516	588	495	607
AUDITORY	ZERO	NMSE	.139	.175	.169	.167
		R_{max}	.949	.939	.933	.957
		τ (in msec)	410	432	294	460
	FIRST	NMSE	.188	.202	.191	.256
		R_{max}	.960	.951	.944	.930
		τ (in msec)	569	613	369	489
	SECOND	NMSE	1.727	1616	2.055	2.321
		R_{max}	.727	.725	.588	.616
		τ (in msec)	1209	1375	1244	1678

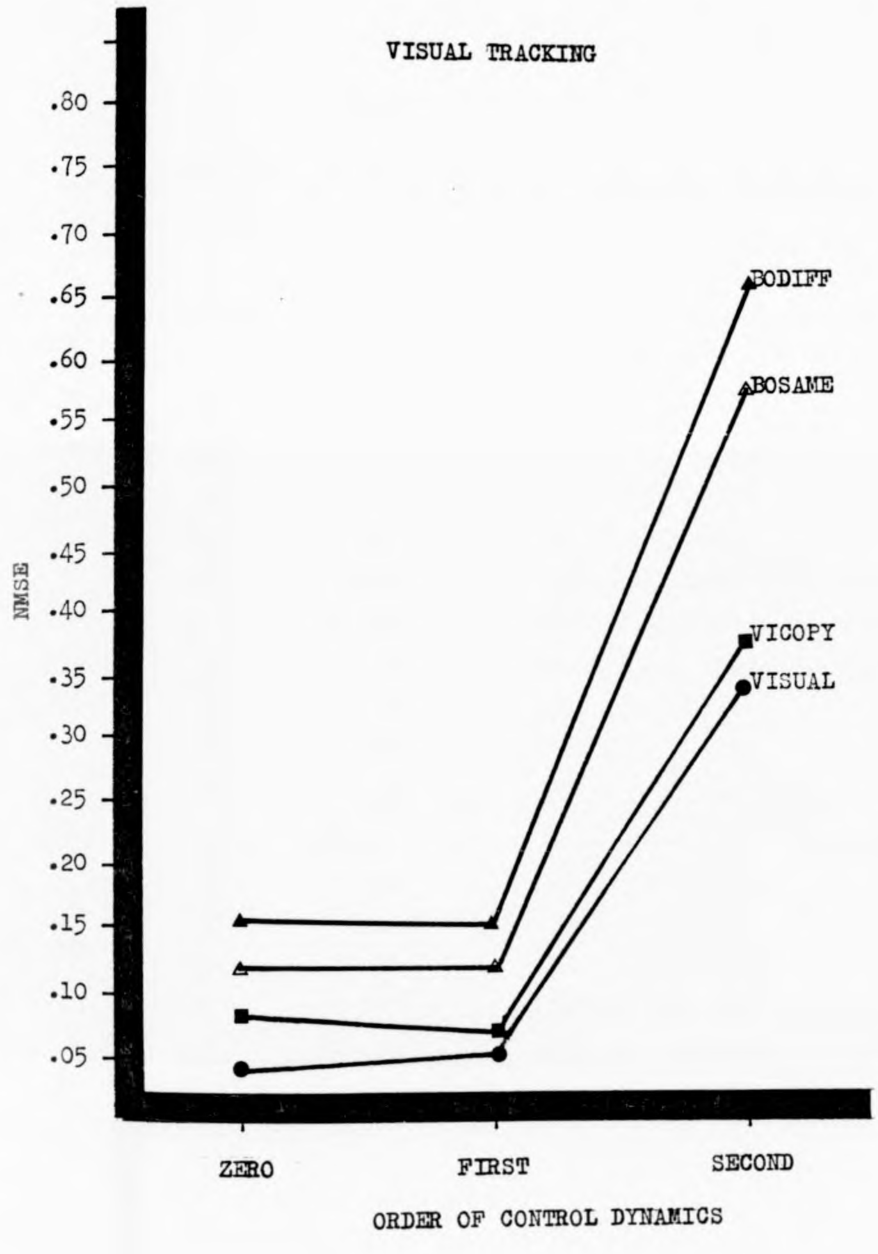

Fig. 5.1.- Normalized mean-squared tracking error in each tracking condition as a function of controlled element dynamics.

TABLE 5.2

Average NMSE in each visual tracking condition as a function of controlled element dynamics. Experiment 2.

CONTROLLED ELEMENT DYNAMICS	S	TRACKING CONDITION VISUAL	VICOPY	BOSAME	BODIFF
ZERO	1	.027	.112	.170	.254
	2	.024	.076	.083	.122
	3	.038	.067	.099	.121
	4	.048	.064	.124	.122
		$\bar{X}$= .034	.080	.119	.155
FIRST	1	.044	.069	.123	.254
	2	.057	.060	.128	.121
	3	.039	.071	.101	.121
	4	.056	.067	.127	.122
		$\bar{X}$= .049	.067	.120	.154
SECOND	1	.341	.444	.581	.892
	2	.327	.356	.327	.714
	3	.321	.325	.539	.302
	4	.346	.369	.847	.728
		$\bar{X}$= .336	.373	.574	.659

Average of 6 trials per cell.

TABLE 5.3

Summary ANOVA table on average visual tracking NMSE in Experiment 2.

SOURCE	DF	SS	MS	F	PROB
Subjects	3	0.072			
Control Order {O}	2	1.609	0.804	82.2365	0.0001
EW1B	6	0.059	0.010		
Conditions {C}	3	0.259	0.086	6.9929	0.0103
EW2B	9	0.111	0.012		
{O x C}	6	0.092	0.015	2.2035	0.0903
EW12B	18	0.126	0.007		
W	44	2.255			
TSQ/N=	2.4661	N= 48	SST=	2.3272	

levels corresponding to zero, first and second order control and (2) a tracking conditions factor with four levels, one for the single-task control condition and three for the time-shared tracking dual-task conditions. A summary ANOVA table is presented in Table 5.3. Average visual tracking NMSE values, computed over trials and subjects, are plotted as a function of controlled element dynamics in Figure 5.1.

Analysis of variance revealed a highly significant order of control main effect. Post hoc multiple mean comparisons using Newman Keuls procedure revealed highly significant contrasts between mean tracking NMSE with second order controlled element dynamics and zero and first order controls ($p<.001$), and no significant difference between the means relating to each of these latter two. That is, overall tracking NMSE for the various tracking conditions was no different with zero order controls (.097) from that with first order controls (.098). When, however, the control dynamics were raised to second order, tracking NMSE increased fourfold to a value of .486. Examination of Table 5.1 reveals this to be a general pattern of results for the various visual and auditory tracking conditions. With progressively higher control dynamics order, corresponding increases in average tracking NMSE are observed. From the table it is clear that the transition from zero order to first order, for both visual and auditory tracking conditions, was less dramatic than the transition from first order to second order. Moreover, this effect was more marked in the VISUAL tracking condition than in the other time-shared tracking conditions. The tracking conditions' main effect was also significant as is indicated in Table 5.3. Average visual tracking NMSE was found to increase significantly with the addition of the auditory tracking task in the BOSAME and BODIFF tracking conditions ($p<.05$ and $p<.01$ respectively), but not significantly so when the additional copying task was introduced. This pattern of results held for zero, first and second order control dynamics individually.

Perusal of Figure 5.1 reveals a uniform pattern of results. Presumably the .86rad/sec forcing function input signal was not very demanding. The transition from zero to first order control, therefore, was easily accommodated with no significant increases in tracking NMSE. The requirement to track and copy simultaneously induced an overall, but insignificant, decrement in task performance relative to the single-task VISUAL tracking condition. When tracking with zero order control, VICOPY tracking NMSE values were considerably greater than those in the VISUAL tracking condition. This difference reduced slightly when first and second order control dynamics were involved.

Examination of Table 5.2 reveals that tracking NMSE in the VICOPY condition relative to that in the VISUAL tracking condition was overall 2.4 times greater. This difference reduced to 1.4 and 0.4 times when the control dynamics were raised to first and second order.

Above the VICOPY condition tracking NMSE curve in Figure 5.1 lie those for the BOSAME and BODIFF tracking conditions. NMSE values were not statistically significant between the BOSAME and BODIFF tracking conditions. In all contrasts, however, the introduction of the auditory tracking task produced highly significant increases in tracking NMSE. The introduction of the copying task for the three orders of control dynamics considered only produced an overall increase in tracking NMSE relative to the VISUAL control condition some 25% greater. A comparable time-sharing increase in tracking NMSE observed when the auditory tracking task was introduced in the BOSAME tracking condition was 95 times greater. It is unlikely, therefore, that response interference effects arising from the requirements to respond using both hands would have produced the observed bimodal compensatory tracking time-shared tracking performance decrements.

The requirement to time-share tracking in the VICOPY, BOSAME and BODIFF conditions produced a pattern of results which was present for zero order, as well as for first, and second order control dynamics.

Auditory Tracking

The auditory tracking NMSE results are less informative, in particular with respect to tracking with second order control dynamics. The subjects all reported finding the second order control auditory tracking conditions fiendishly difficult to perform. The Experimenter persevered to collect second order control tracking data, even though it was evident that the results would be questionable.

Mean auditory tracking NMSE computed over trials and subjects is plotted as a function of controlled element dynamics in Figure 5.2. Individual subject data in each tracking condition and order of controlled element dynamics are presented in Table 5.4. These data were submitted to a

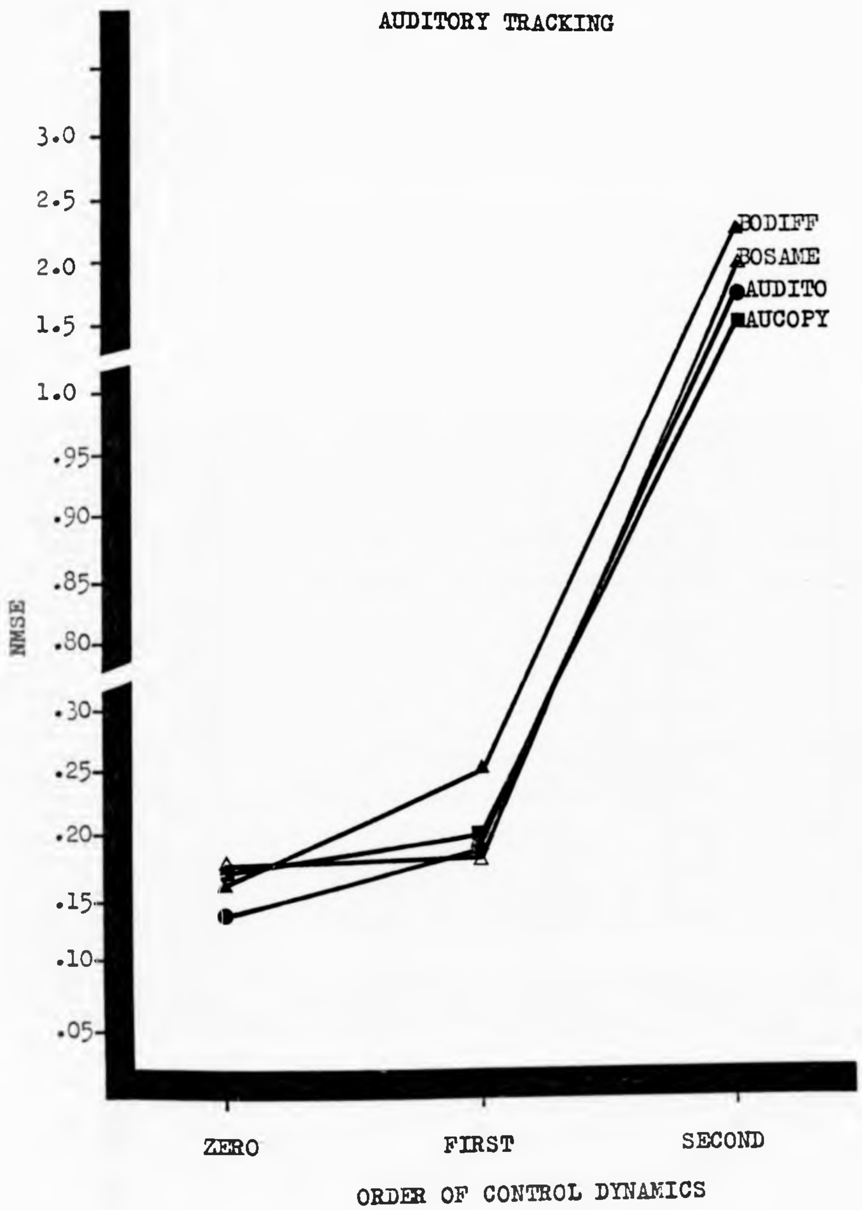

Fig. 5.2.- Normalized mean-squared tracking error in each tracking condition as a function of controlled element dynamics.

TABLE 5.4

Average NMSE in each auditory tracking condition as a function of controlled element dynamics. Experiment 2.

CONTROLLED ELEMENT DYNAMICS	S		VISUAL	VICOPY	BOSAME	BODIFF
			TRACKING CONDITIONS			
ZERO	1		.145	.153	.087	.162
	2		.066	.146	.185	.181
	3		.087	.137	.116	.168
	4		.257	.264	.289	.155
		$\bar{X}$=	.139	.175	.169	.167
FIRST	1		.170	.184	.175	.229
	2		.115	.170	.104	.146
	3		.181	.167	.169	.289
	4		.286	.287	.315	.361
		$\bar{X}$=	.188	.202	.191	.256
SECOND	1		1.578	1.107	2.070	2.932
	2		1.499	.989	2.618	2.500
	3		2.081	1.690	1.710	2.051
	4		1.750	1.676	1.820	1.800
		$\bar{X}$=	1.727	616	2.055	2.321

erage of 6 trials per cell.

TABLE 5.5

Summary ANOVA table on average auditory tracking NMSE in Experiment 2.

SOURCE	DF	SS	MS	F	PROB
Subjects	3	0.037			
Control Order {O}	2	32.443	16.222	254.0650	0.0001
EW1B	6	0.383	0.064		
Conditions {C}	3	0.486	0.162	2.6330	0.1133
EW2B	9	0.554	0.062		
{O x C}	6	0.762	0.127	2.2737	0.0823
EW12B	18	1.006	0.056		
W	44	35.635			
TSQ/N=	28.2440	N= 48		SST=	35.6712

two-way repeated measures analysis of variance. A summary ANOVA table is presented in Table 5.5.

Examination of Table 5.5 reveals that only the control order main effect was significant. Increasing the order of control from zero to first order did not produce a satistically significant relative increase in tracking NMSE. Relative increases in NMSE were observed, however, in all the conditions and all the subjects except for subject 2 whose auditory tracking NMSE was slightly higher in the BOSAME tracking condition with zero order controls. When the control dynamics were raised to second order the subjects could not master the auditory tracking task. Despite their cooperation in doubling the training period from two to four sessions, it is evident from perusal of Table 5.4 that the subjects could barely manage to keep the tracking task stable,generating more tracking error than if they simply jittered the joystick about the zero output signal reference. The tracking conditions main effect was, therefore, not significant. Individual one-way repeated measures ANOVA on the tracking conditions factor,for each order of control,revealed that NMSE varied significantly with tracking condition when first order controls were involved. Only the contrast between the AUDITORY tracking task and the BODIFF tracking task was significant. Nevertheless, though the auditory tracking NMSE results are rather variable, hints of decrements in task performance associated with the requirement to time-share tracking could be discerned. Apparently, the auditory localizing abilities of subjects in tracking the second order control dynamics were being overtaxed. The subjects tried their best, but often would comment that they had lost all control for both tasks and had to start all over again. It is not certain what the effects of extended practice would be in second order auditory tracking. The subjects noticed that in attempting to control the visual and auditory inputs simultaneously they often had to make incompatible response movements with respect to those of the track, and on other occasions they did not. Soon confusion set in, and rather than reducing error they would be adding to it. Yet it is clear from Table 5.2 that they were, nevertheless, able to track the visual display in conjunction with the auditory display. The possibility remains, therefore, that the visual tracking task was favored at the expense of the auditory tracking task so as to keep at least one task marginally stable.

Analysis of Tracking Linearity, R_{max}, Measures

Visual Tracking

Average visual tracking linearity measures, R_{max}, computed over trials and subjects, for each tracking condition, are plotted as a function of controlled element dynamics in Figure 5.3. Individual subject data are presented in Table 5.6. These data were then submitted to a two-way repeated measures analysis of variance. A summary ANOVA table is presented in Table 5.7.

Both the control order and tracking conditions main effects were significant; the two-way interaction, however, was not. Tracking linearity was not found to vary significantly when the control dynamics were changed from zero order to first order, but it was found to reduce considerably when the control dynamics were raised to second order. Overall, subjects found tracking with acceleration control dynamics considerably more difficult than tracking with proportional and with rate controls. This difficulty was reflected by a decrease in tracking linearity and a corresponding increase in tracking NMSE. In addition, tracking linearity was also found to vary with tracking condition.

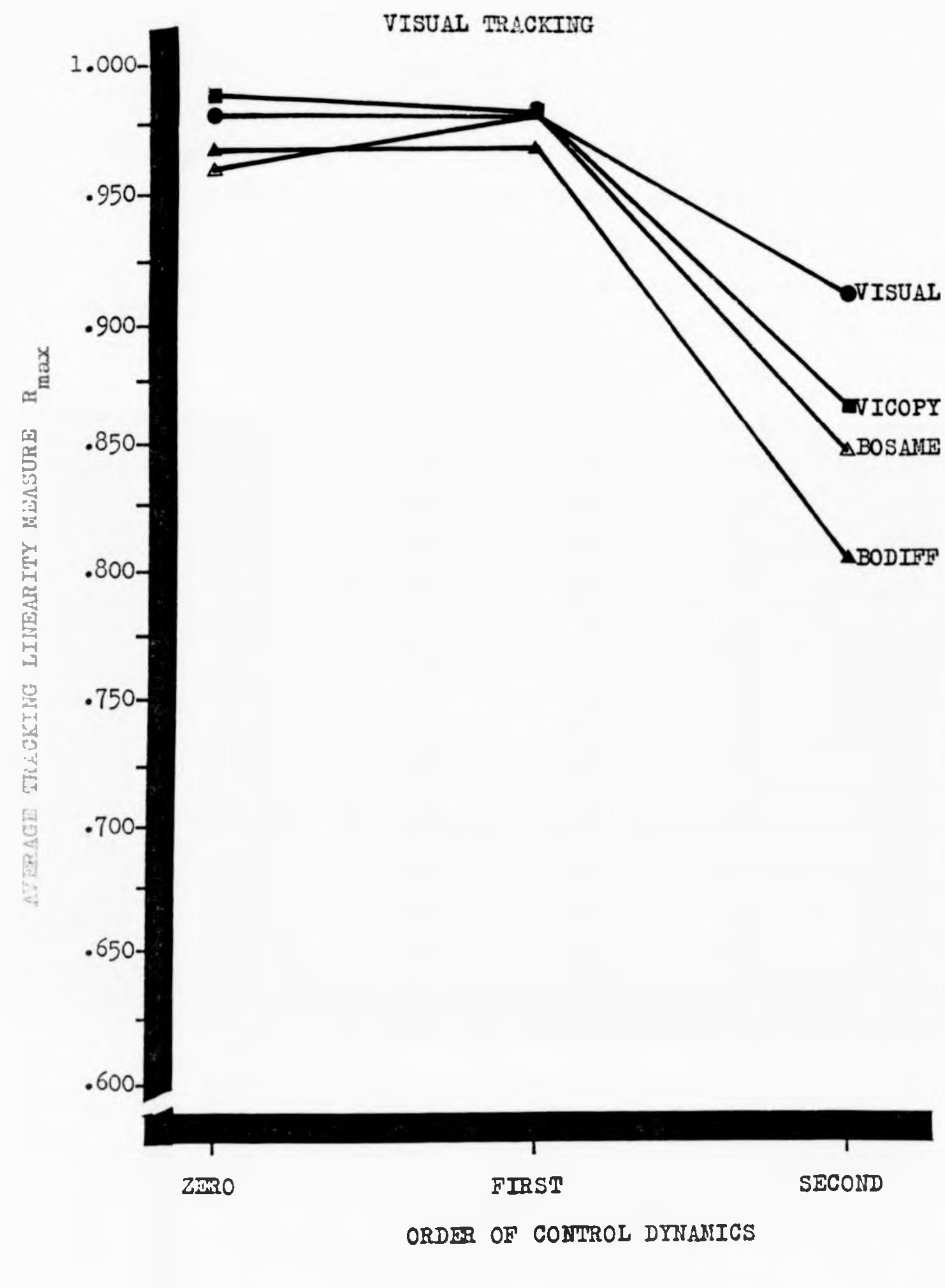

Fig. 5.3.- Tracking linearity measure R_{max} in each tracking condition as a function of controlled element dynamics.

TABLE 5.6

Average visual tracking linearity index, R_{max}, for each tracking condition as a function of controlled element dynamics. Experiment 2.

CONTROLLED ELEMENT DYNAMICS	S	TRACKING CONDITION			
		VISUAL	VICOPY	BOSAME	BODIFF
ZERO	1	.946	.989	.943	.944
	2	.996	.984	.954	.984
	3	.994	.988	.984	.974
	4	.982	.984	.969	.975
	$\bar{X}$=	.980	.986	.963	.969
FIRST	1	.974	.985	.985	.930
	2	.995	.993	.980	.982
	3	.972	.979	.985	.987
	4	.986	.981	.979	.981
	$\bar{X}$=	.982	.984	.982	.970
SECOND	1	.852	.772	.819	.703
	2	.944	.851	.928	.796
	3	.928	.919	.877	.922
	4	.919	.921	.777	.808
	$\bar{X}$=	.911	.866	.850	.807

Average of 6 trials per cell.

TABLE 5.7

Summary ANOVA table on average visual tracking linearity measure, R_{max}, in Experiment 2.

SOURCE	DF	SS	MS	F	PROB
Subjects	3	0.021			
Control Order {O}	2	0.150	0.075	28.9189	0.0012
EW1B	6	0.016	0.003		
Conditions {C}	3	0.012	0.004	3.9011	0.0488
EW2B	9	0.009	0.001		
{O x C}	6	0.012	0.002	2.0497	0.1109
EW12B	18	0.018	0.001		
W	44	0.216			

TSQ/N= 42.1875 N= 48 SST= 0.2370

This effect, however, was only significant in the contrast relating the average R_{max} values in the VISUAL and BODIFF tracking conditions ($p < .001$). Moreover, this effect was observed only when subjects tracked with second order controls. Examination of Figure 5.3 reveals R_{max} values to be highest in the VISUAL and lowest in the BODIFF tracking conditions. For zero and first order control, these differences are not as marked as for second order control, where the R_{max} values associated with the various tracking conditions seem to fan out encompassing a greater range as tracking performance deteriorates. Since the .86rad/sec tracking input bandwidth was relatively low, it is conceivable that the tracking tasks were not made all the more difficult by the raise from zero order to first order control. If we turn to Table 4.7 in Experiment 1, we note that for the .86rad/sec signal tracking linearity was slightly lower than that observed in this experiment, where in both cases first order control dynamics were involved. When the controlled element dynamics were raised to second order the tasks were now much more difficult to perform and clear time-sharing decrements in tracking linearity begin to show.

Auditory Tracking

Average R_{max} values, computed over trials and subjects in each tracking condition, are plotted in Figure 5.4. Individual subject data in the various tracking conditions and control element dynamics investigated are presented in Table 5.8. These data were then submitted to analysis of variance. A summary ANOVA table is presented in Table 5.9. There were two chief factors in the analysis, one repeated measures factor relating to order of control, and another repeated measures factor relating to tracking condition.

Examination of Table 5.9 reveals that the order of control main effect was highly significant, as was the tracking conditions main effect. The two-way order of control by tracking condition interaction was also highly significant. The contrast between the means for auditory tracking linearity measures, R_{max}, was not found to vary consistently when the control dynamics were raised from zero to first order. A marked reduction in tracking linearity was observed, however, when the dynamics of the controls were raised from first order to second order. The result confirms that observed in the visual tracking conditions. There are, however, two differences: firstly, the BODIFF tracking condition for zero order control actually yielded the highest tracking linearity measure, whereas, for the first order control treatment, we note it to be the

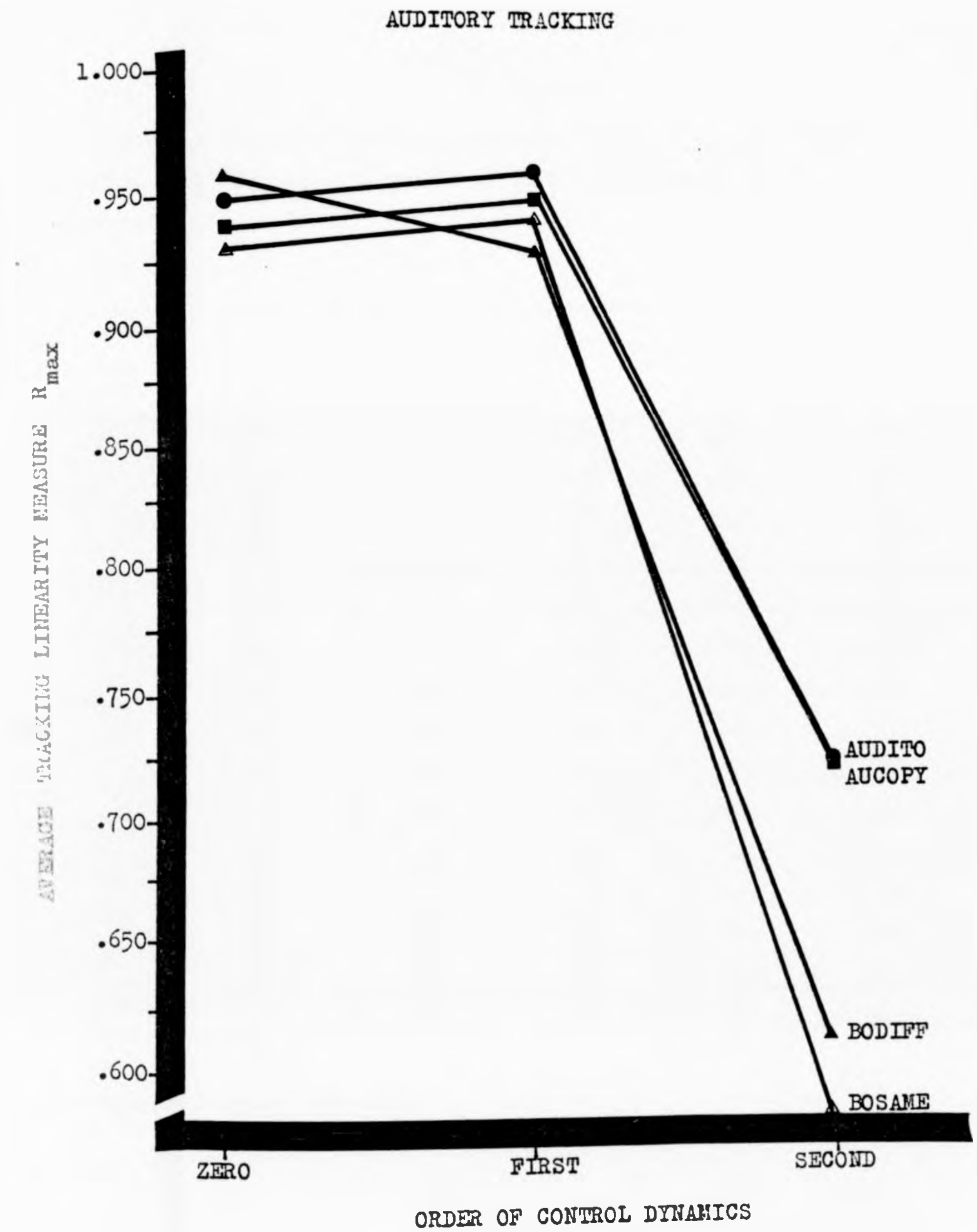

Fig. 5.4.- Tracking linearity measure R_{max} in each tracking condition as a function of controlled element dynamics.

TABLE 5.8

Average auditory tracking linearity index, R_{max}, for each tracking condition as a function of controlled element dynamics. Experiment 2.

CONTROLLED ELEMENT DYNAMICS	S		TRACKING CONDITION AUDITO	AUCOPY	BOSAME	BODIFF
ZERO	1		.949	.957	.969	.966
	2		.983	.954	.917	.945
	3		.979	.977	.958	.956
	4		.885	.868	.888	.960
		$\bar{X}$=	.949	.939	.933	.957
FIRST	1		.965	.967	.952	.943
	2		.973	.967	.963	.961
	3		.954	.946	.948	.912
	4		.948	.924	.912	.902
		$\bar{X}$=	.960	.951	.944	.930
SECOND	1		.698	.763	.649	.660
	2		.768	.698	.507	.484
	3		.663	.724	.610	.697
	4		.778	.713	.585	.623
		$\bar{X}$=	.727	.725	.588	.616

verage of 6 trials per cell.

TABLE 5.9

Summary ANOVA table on average auditory tracking linearity measure, R_{max}, in Experiment 2.

SOURCE	DF	SS	MS	F	PROB
Subjects	3	0.010			
Control Order {O}	2	0.846	0.423	129.8450	0.001
EW1B	6	0.020	0.003		
Conditions {C}	3	0.028	0.009	5.5930	0.0194
EW2B	9	0.015	0.002		
{O x C}	6	0.038	0.006	4.2874	0.0075
EW12B	18	0.027	0.001		
W	44	0.973			

TSQ/N= 34.8008 N= 48 SST= 0.9834

lowest; thus returning to its more familiar ranking. A partial answer for this result is given in Table 5.12. If we turn to the BODIFF tracking condition column with zero order control dynamics, we note that the average response values of τ are considerably longer than those in the BOSAME tracking condition. Compared to the corresponding values in the first order control treatment we note a tendency for τ to be reduced with the addition of the visual task. Alternatively, the effect may be due to random variation in the data. Secondly, we note that, whereas the BOSAME condition usually yielded better tracking accuracy than that observed in the BODIFF tracking condition, on this occasion R_{max} was lowest when the subjects tracked using the second order controls. Because of the rather poor tracking performance observed for these conditions, it is conceivable that this interaction may be due to the considerable amount of noise in the data. Other than point to the reduced measures in this condition recorded in Table 5.12, no obvious other explanation can account for this discrepancy. But, taken in conjunction with the decrease in tracking linearity also observed in the BODIFF tracking condition, a sizeable time-sharing decrement in tracking linearity is evident.
Once more, for both zero and first order control, these time-sharing decrements may have been minimized by the low tracking

input bandwidth used.

There was no evidence from examination of the crosscorrelation function relating the subjects' response control command signals $c_v(t)$ and $c_a(t)$ that the subjects were considering only one of the signals when performing the BOSAME tracking condition. A comparison between the crosscorrelation peak values and their time of occurrence for the BOSAME, AUCOPY and VICOPY tracking conditions suggests that the subjects were deriving information from both tracking error signals when carrying out the BOSAME tracking conditions. These data are presented in Table 5.15. The table shows average cross-correlation peak values to be considerably higher in the VICOPY and AUCOPY conditions than in the BOSAME tracking condition. This is particularly true for the first and second order controlled element dynamics. The finding that the relative phase difference between the response signals in the BOSAME tracking conditions is usually greater than that in the other two conditions adds further support to the notion that the subjects were not simply tracking one signal and copying the response with the other hand.

Analysis of Average Tracking Response Delay τ Measures

Visual Tracking

Average visual tracking response delay τ measures were computed over trial replications for each subject individually in each tracking condition and for the zero, first and second order controlled element dynamics investigated. These data, presented in Table 4.10, were submitted to a two-way repeated measures analysis of variance comprising (1) an order of control main effect with three levels corresponding to zero, first and second order, and (2) a tracking conditions main effect with four levels corresponding to the single-task VISUAL condition and the VICOPY, BOSAME and BODIFF time-sharing conditions. A summary ANOVA table is presented in Table 4.11. Mean τ values, computed over trial replications and subjects, are plotted as a function of controlled element dynamics in Figure 5.5.

Examination of Table 5.11 reveals that the order of control dynamics' main effect was not statistically significant. Nevertheless, it should be noted that overall increasing the order of control dynamics from zero to first order increased overall τ measures by 20%. These were further increased relative to zero order by 58% when the control dynamics were raised to second order.

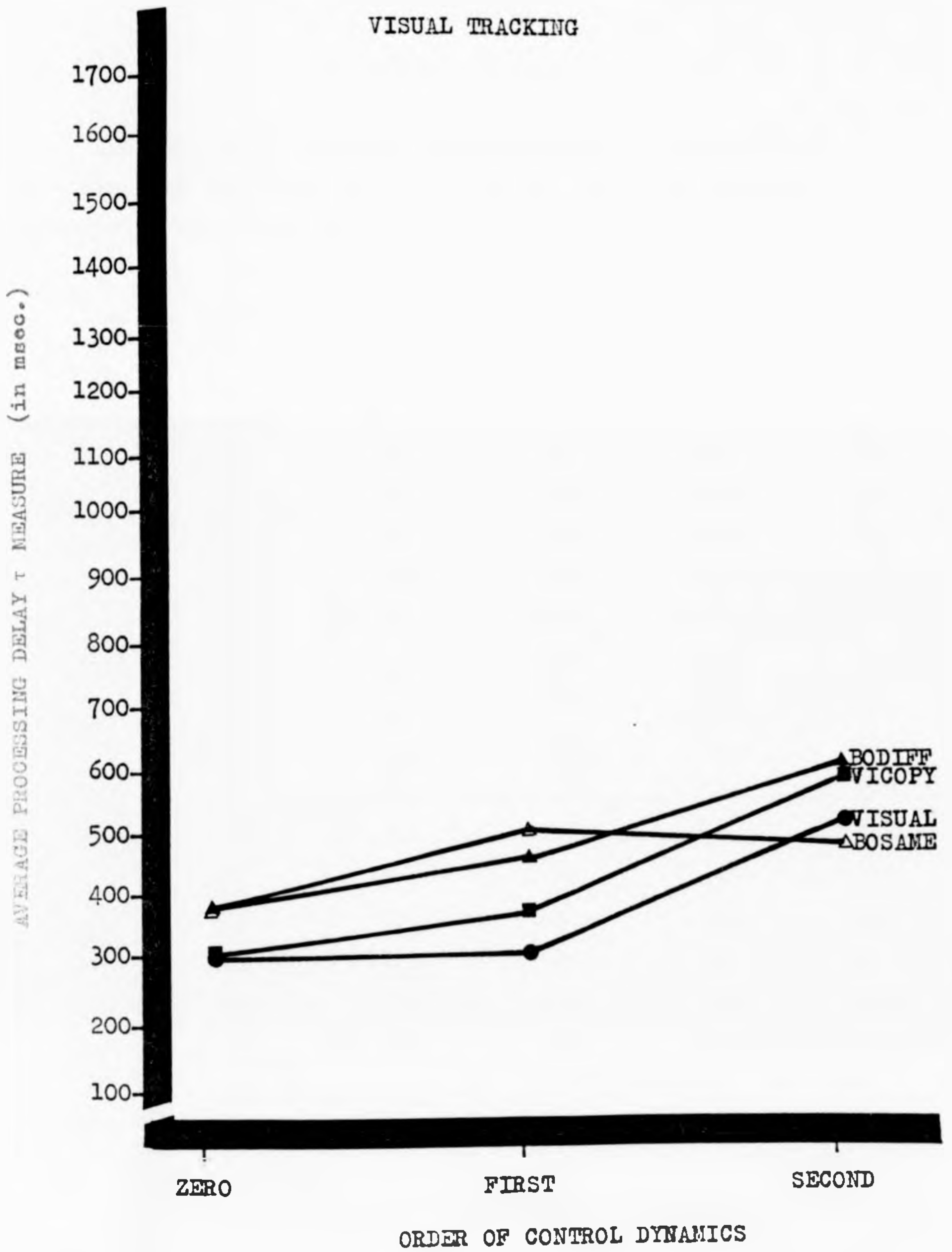

Fig. 5.5.- Average processing delay τ measure in each tracking condition as a function of controlled element dynamics.

TABLE 5.10

Average visual tracking response delay, τ, measure for each tracking condition as a function of controlled element dynamics. Experiment 2.

CONTROLLED ELEMENT DYNAMICS	S		TRACKING CONDITION		
		VISUAL	VICOPY	BOSAME	BODIFF
ZERO	1	388	300	363	238
	2	225	338	338	350
	3	288	313	400	475
	4	325	313	438	488
	$\bar{X}$=	307	316	385	388
FIRST	1	325	376	450	388
	2	363	363	625	500
	3	288	388	463	525
	4	300	376	488	488
	$\bar{X}$=	319	376	507	475
SECOND	1	775	638	650	1050
	2	413	800	538	563
	3	488	425	450	275
	4	388	488	338	538
	$\bar{X}$=	516	588	494	607

verage of 6 trials per cell.

TABLE 5.11

Summary ANOVA table on average visual tracking response delay, τ, measure in Experiment 2.

SOURCE	DF	SS	MS	F	PROB
Subjects	3	67058.000			
Control Order {O}	2	337550.000	168775.000	3.3420	0.1055
EW1B	6	303004.000	50500.668		
Conditions {C}	3	80141.000	26713.666	4.2309	0.0401
EW2B	9	56826.000	6314.000		
{O x C}	6	68940.000	11490.000	0.9683	0.5254
EW12B	18	213600.000	11866.667		
W	44	1060061.000			

TSQ/N= 9277846.0000 N= 48 SST= 1127119.0000

The tracking conditions' main effect, however, was significant. A significant 29% increase ($p<.01$) in was induced by the requirement to perform the BODIFF tracking condition relating to the VISUAL single-task control condition. The effect was less marked, 21% ($p<.05$), when the subjects performed the BOSAME tracking condition. The additional copying task in the VICOPY tracking condition produced an increase (n.s.) of 12% in τ, approximately half that of the two other time-sharing tasks. The tracking condition main effect, however, could be statistically attributable only to the tracking conditions performed with first order control dynamics. Examination of Table 5.10 reveals, however, that the general pattern of results was present in all the controlled element dynamics considered. The requirement to time-share tracking in almost all instances produced an increase in τ. This increase in τ, however, could not entirely be attributable to response interference, and may be thought to reflect instead attentional limitations in multitask information processing activity.

Auditory Tracking

Average auditory tracking response delay τ measures, in each tracking condition, for each subject individually and for zero, first and second order control dynamics are presented in Table 5.12 These values, averaged over subjects, were plotted as a function of order of control and are presented in Figure 5.6. Individual subject τ means were subjected to a two-way repeated measures analysis of variance. A summary ANOVA table representing the order of control and tracking conditions factors, and their interaction, is given in Table 5.13.

Only the control order main effect was statistically significant. The contrast relating mean τ values in the zero and first control order treatments was not significant, but the contrasts relating these two orders of control to second order were highly so ($p<.001$). Raising the controlled element dynamics from zero order to first order produced a 111msec average increase in τ. Raising the order of control once more to second order increased the average τ values 510msec to 1377msec, an increase of 978msec relative to zero order control. Examination of Table 5.12 reveals the pattern of results to be well represented in most subjects. Although the auditory tracking τ values with second order controls are, however, very variable and may prohibit the extraction of meaningful relationships, the overall pattern of results for the various conditions does indicate an increase in τ with time-sharing. The effect is less marked when subjects performed the BOSAME tracking condition, but, nevertheless, τ was

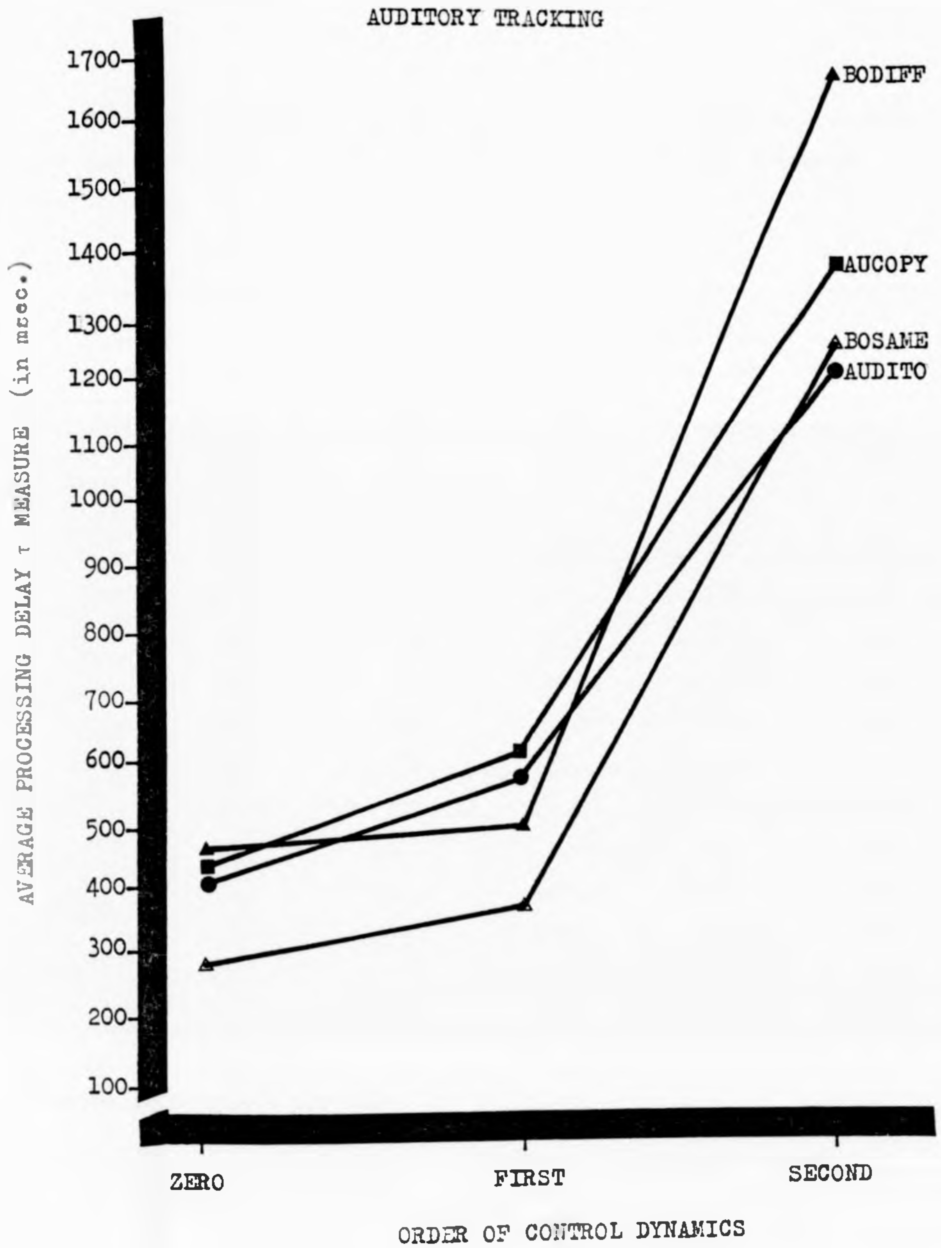

Fig. 5.6.- Average processing delay τ measure in each tracking condition as a function of controlled element dynamics.

TABLE 5.12

Average auditory tracking response delay, τ, measure for each tracking condition as a function of controlled element dynamics. Experiment 2.

CONTROLLED ELEMENT DYNAMICS	S		TRACKING CONDITION AUDITO	AUCOPY	BOSAME	BODIFF
ZERO	1		388	338	225	475
	2		388	475	263	438
	3		488	475	313	475
	4		375	439	375	450
		$\bar{X}=$	410	432	294	460
FIRST	1		650	562	388	538
	2		438	613	275	463
	3		400	325	200	388
	4		788	950	613	567
		$\bar{X}=$	569	613	369	489
SECOND	1		1013	867	825	1987
	2		1525	1975	1200	1662
	3		1000	1021	938	1413
	4		1300	1637	2013	1650
		$\bar{X}=$	1210	1375	1244	1678

Average of 6 trials per cell.

TABLE 5.13

Summary ANOVA table on average auditory tracking response delay, τ, measure in Experiment 2.

SOURCE	DF	SS	MS	F	PROB
Subjects	3	673330.000			
Control Order {O}	2	9173228.000	4586614.000	42.1351	0.0005
EW1B	6	653130.000	108855.000		
Conditions {C}	3	382430.000	127476.664	2.0524	0.1765
EW2B	9	558992.000	62110.223		
{O x C}	6	363634.000	60605.668	1.8286	0.1494
EW12B	18	596580.000	33143.332		
W	44	11727994.000			

TSQ/N= 27851104.0000 N= 48 SST= 12401324.0000

found to increase from 1210msec for the AUDITORY task to 1375msec for the AUCOPY tracking task, and again to 1678msec for the BODIFF tracking task. Only a 35msec time-sharing increase was noted when the subjects performed the BOSAME tracking condition. If subjects were decreasing average τ at the expense of a loss in tracking accuracy, this tradeoff would be indicated by reduced R_{max} values in this condition. Turning to Table 5.8 we note that indeed the BOSAME R_{max} values were the lowest. It is conceivable that the subjects faced with an extremely demanding dual-task were responding more rapidly to the changes in perceived auditory tracking error, perhaps engaging in a bang-bang strategy whereby the control is moved from one side to the other. This strategy would increase tracking remnant (decrease R_{max}), increase overall NMSE, reduce τ, and have the added advantage of keeping the control system at least marginally stable. For first and zero order controls auditory τ does not appear to increase in regular monotonic fashion with the additional copying and visual tracking tasks. We note also that zero order control τ in the BOSAME tracking conditions was less than in the comparable BODIFF tracking conditions. Turning once more to Table 5.8 we observe R_{max} to be lowest in this condition, giving rise to an average NMSE value in Table 5.4 that is as great as that in the BODIFF tracking condition. This pattern, however, was not observed when the control dynamics were first order.

Correlation Between the Absolute Tracking Error Signals $e_v(t)$ and $e_a(t)$

The average correlation coefficient relating the absolute visual and auditory tracking error signals for each subject in the BOSAME and BODIFF tracking conditions and for the zero, first and second order control dynamics investigated are presented in Table 5.14.

The most salient feature of the data was the absence of consistent and significant negative correlation between the absolute tracking error signals in the BOSAME and BODIFF tracking conditions, regardless of order of control dynamics. There was no evidence of an increase in the frequency of significant negative correlations existing between the absolute tracking error signals as the order of control dynamics was raised from zero to first and to second order even though presumably the time-shared visual and auditory tracking tasks became more difficult to carry out. It is noteworthy, however, that three of four subjects actually showed significant positive correlation between the absolute tracking error signals in the BOSAME tracking conditions with zero order control dynamics. Since in this tracking

TABLE 5.14

Average correlation coefficient, r, between the absolute tracking error signals, $e_v(t)$ and $e_a(t)$, in the BOSAME and BODIFF tracking conditions. Experiment 2.

ORDER OF CONTROLLED ELEMENT DYNAMICS	S	TRACKING CONDITION BOSAME	BODIFF
ZERO	1	.060	.027
	2	.179	-.122
	3	.275	.095
	4	.330	.144
		$\bar{X}$= .211	.036
FIRST	1	-.047	.009
	2	.062	.096
	3	-.006	-.047
	4	-.182	.005
		$\bar{X}$= -.043	.016
SECOND	1	-.037	.015
	2	.041	.235
	3	.058	.097
	4	-.059	.118
		$\bar{X}$= .001	.116

Average of 6 trials per cell.

condition identical forcing function signals were involved, simultaneous error-reducing demands would be made on the subjects at any one moment. Hence, if subjects were capable of tracking only one input at a time, it would be in this condition that such an inverse relationship would be expected to show.
If, on the other hand, the subjects could perform the tracking tasks simultaneously, quite independently of each other, some positive correlation between the absolute tracking error signals could not be entirely ruled out. High positive correlation coefficients in this condition would only be expected if it was further assumed that both the R_{max} and the τ parameters were the same in both tasks. Since the correlation coefficients were calculated on sampled tracking error signal data collected at a rate of 10 per sec, and, furthermore, since the forcing function input bandwidth was only .86rad/sec, it is unlikely that an inverse relationship between the absolute tracking error signals would have gone undetected. However, if the subjects were to be processing information from each error signal simultaneously and tracking each signal on its own as separated inputs, simultaneous error-reducing activity could not, therefore, be entirely ruled out. The result would be that tracking error between the tracking loops would on occasion be more likely to increase and decrease in unison. Such a functional relationship would

thus be indicated by a positive correlation coefficient. If the subjects were behaving as true limited capacity parallel information processors, tracking error signal inputs would be processed independently of each other, and, therefore, error reducing activity would proceed independently between the loops. This would only be true up to a point, however ,reflecting limitations in information processing capacity. Hence, if such limits were to be exceeded on occasion, error reduction might not take place in either loop until the overload is dissipated. Such overloads might well lead to simultaneous increases in error between the loops. If we look at the correlation coefficients in the conditions in which subjects' information processing ability seemed to be most taxed, i.e. second order control, we note significant positive correlations, but only in the BODIFF tracking condition. Though these correlations proved statistically significant, they may not be very informative. We note that the highest correlation coefficient observed, that of +.330 for zero order control in the BOSAME tracking condition, enables prediction of only about 10% of the variability of one error signal attributable directly to the other error signal. Note that the correlation values for first order control recorded in this experiment were based on six trial observations whereas those recorded in these same conditions in Experiment 1 were computed over twenty trials. Whether with increased sample size the average correlation between the absolute tracking error signals $e_v(t)$ and $e_a(t)$ would have tended to a non-significant, near-zero value is not certain. What is certain is that as the order of the controlled element dynamics was raised the correlation between the absolute tracking error signals did not correspondingly go negative indicating the initiation of serial, switching, task performance.

Crosscorrelation Peak Values between the Control Command Signals $c_v(t)$ and $c_a(t)$

The crosscorrelation function relating the subject's control command signals $c_v(t)$ and $c_a(t)$ was examined and the peak value and time of occurrence for fifty 100-msec lags was recorded on each trial. Average correlation peak values and relative lag between the signals for each subject, the BOSAME, VICOPY and AUCOPY tracking conditions for zero, first and second order control are presented in Table 5.15. Examination of the table indicates that the correlation coefficient relating the signals falls drastically with order of control only in the BOSAME tracking condition. Moreover, the crosscorrelation peak values in the BOSAME condition were considerably lower than those in the VICOPY and AUCOPY conditions. This difference was not so marked for zero order control, but the relative phase difference between the signals was some 107msec greater than that in the other two

TABLE 5.15

Average crosscorrelation peak values, R_{max}, and average relative lag, τ, between the subject's command control response signals $c_v(t)$ and $c_a(t)$ in the BOSAME, VICOPY and AUCOPY tracking conditions. Experiment 2.

ORDER OF CONTROLLED ELEMENT DYNAMICS	S	BOSAME R_{max}	BOSAME τ (msec)	VICOPY R_{max}	VICOPY τ	AUCOPY R_{max}	AUCOPY τ
ZERO	1	.918	113	.963	000	.918	000
	2	.897	163	.950	000	.958	000
	3	.942	88	.962	000	.963	000
	4	.870	63	.910	000	.934	000
	$\bar{X}$=	.906	107	.946	000	.943	000
FIRST	1	.639	100	.935	000	.930	000
	2	.705	25	.915	000	.972	000
	3	.784	25	.953	000	.956	000
	4	.602	250	.940	000	.922	000
	$\bar{X}$=	.683	100	.936	000	.929	000
SECOND	1	.313	130	.963	000	.958	000
	2	.207	188	.898	000	.944	000
	3	.216	750	.951	000	.951	000
	4	.000	438	.977	000	.963	000
	$\bar{X}$=	.184	377	.947	000	.954	000

verage of 6 trials per cell.

conditions. The notion that subjects were tracking the forcing functions as distinct inputs in the BOSAME tracking conditions is less plausible when zero order control dynamics were involved. This is because, overall,the differences in both response delay and crosscorrelation function peak values between the control command signals $c_v(t)$ and $c_a(t)$ in the BOSAME tracking condition were more similar to those in the VICOPY and AUCOPY tracking conditions. When first and second order control dynamics were introduced, however, it is evident that the subjects were not engaging in a tracking /copying stratagem when performing the BOSAME tracking condition. Both the crosscorrelation function peak values and average relative lag between the $c_v(t)$ and $c_a(t)$ signals in this condition were reliably different from those observed in the VICOPY and AUCOPY tracking conditions.

DISCUSSION

The results of this experiment indicate in more or less general terms that the time-shared tracking effects observed in Experiment 1 with input bandwidth variation generalize as well to zero, first and second order control dynamics. Moreover, they confirm in more ways than one those observed in Experiment 1. The requirement to time-share tracking between conditions. The notion that subjects were tracking the forcing functions as distinct inputs in the BOSAME tracking conditions is less plausible when zero order control dynamics were involved. This is because, overall,the differences in both response delay and crosscorrelation function peak values between the control command signals $c_v(t)$ and $c_a(t)$ in the BOSAME tracking condition were more similar to those in the VICOPY and AUCOPY tracking conditions. When first and second order control dynamics were introduced, however, it is evident that the subjects were not engaging in a tracking/copying stratagem when performing the BOSAME tracking condition. Both the crosscorrelation function peak values and average relative lag between the $c_v(t)$ and $c_a(t)$ signals in this condition were reliably different from those observed in the VICOPY and AUCOPY tracking conditions.

DISCUSSION

The results of this experiment indicate in more or less general terms that the time-shared tracking effects observed in Experiment 1 with input bandwidth variation generalize as well to zero, first and second order control dynamics. Moreover, they confirm in more ways than one those observed in Experiment 1. The requirement to time-share tracking between the visual and auditory modalities produced a general decrement in tracking performance. The introduction of the copying task, however, did not produce a significant decrement in tracking performance that would be comparable to that observed in the bimodal tracking tasks. Nevertheless, given the low bandwidth of the forcing functions, it is not possible to dismiss entirely response interference, because consistent, though minor, interference effects were noted in the VICOPY as well as the AUCOPY conditions. This result does suggest, however, that some interference did arise from the requirement to emit simultaneous responses to one input, but that such interference, attributable largely to response competition, was not as severe as that observed when attention had to be divided between the visual and auditory inputs. Since obvious factors such as within-modality interference and memory load can be disregarded as potential contributors of tracking error, it is conceivable that the observed limitations in processing were in effect arising as a natural consequence of subjects' inability to allocate full attention to the tasks. The size of the time-sharing decrements observed were magnified several times by the transition from first to second order control. The various contrasts made between zero and first order control performance revealed that the transition from zero to first order was nowhere as great as that from first to second order. The low forcing function bandwidth was probably too easy to control to cause significant differences in tracking performance between the zero and first order controls. When second order controls were involved, however, the tracking tasks were considerably more difficult to perform, and this was particularly true for auditory tracking, where, in effect, subjects were generating more tracking error in attempting to track the forcing function than would have been generated had they simply worked to keep the joystick output voltage to a minimum; but even here, if we examine Table 5.1, we clearly observe considerably greater tracking error, reduced tracking linearity and increased response delay in the bimodal time-shared tracking tasks relative to single-task performance.

In agreement with the results obtained in Experiment 1, the correlation coefficient relating the absolute tracking error signals in the BOSAME and BODIFF tracking conditions do not indicate any evidence of a transition from parallel to serial error-reducing activity as the order of controlled element dynamics is raised from zero to first and from first to second order. This was so even though it was evident that for second order control dynamics these tasks were most (frustratingly) difficult. There was also a hint, but only for two subjects, of positive correlation between the absolute tracking error signals, but whether this effect was due to "state correlation" (see Garner and Morton, 1969), simultaneous processing or neither of these, is not certain. Nor is it wise to speculate on comparable data for second order control, given the rather poor auditory tracking performance observed. It would thus appear that the subject's error-reducing activities were tied neither to the forcing functions nor to the magnitude of error between the loops in any obvious way.

It is interesting to note the interplay between tracking linearity R_{max} and response delay τ measures. Consider, for example, visual tracking R_{max} and τ measures with first order control dynamics in the BOSAME and BODIFF tracking conditions. These data are presented in Table 5.1. Visual tracking NMSE is considerably higher in these conditions than that in the single-task VISUAL and time-shared VICOPY tracking conditions. This difference in tracking NMSE between single-task and dual-task bimodal compensatory tracking can be attributed to a relative decrement in tracking linearity only in the BODIFF tracking condition. R_{max} values in the VISUAL tracking condition are comparable to those in the BOSAME tracking condition. When τ measures are examined instead, we note an opposite pattern of results. The difference in average tracking NMSE between single-and dual-task bimodal tracking conditions may now be only attributable to a relative increase in τ with time sharing, but only in the BOSAME tracking condition.

A similar relationship between NMSE, R_{max} and τ measures is observed for auditory tracking with zero order control dynamics. NMSE in the time-shared bimodal conditions was once more considerably greater than in the single-task AUDITORY tracking condition. However, whereas R_{max} measures were greater in the BODIFF tracking condition relative to those in the BOSAME condition, this increase in tracking linearity was achieved at a distinct cost in τ, thus serving to increase tracking NMSE to a level comparable to that observed in the BOSAME tracking condition.

It is early days yet, but such interplay between R_{max} and τ measures in producing time-sharing decrements in tracking performance could in future be of importance; it could perhaps be used as an index of whether the requirement to divide attention between certain kinds of tasks affects tracking linearity or average processing delay in selective ways while others do not.

CHAPTER 6.

6.1 - Experiment 3: Homogeneous and Heterogeneous Inputs, Homogeneous Control Dynamics

The primary object of this experiment, and also that of Experiment 4, was to decide between two alternative hypotheses. Both of these hypotheses and their implications have been described and discussed in Chapter 1, and relate specifically to the differentiated or indifferentiated nature of human attentional resources or capacity. One view holds that attentional resources are differentially allocated to two concurrently performed tasks in finite amounts, fixed by the separate attentional demands inherent to each task. The other holds that the performance of a given task does not depend in absolute terms on its informational load but rather on the relative attentional resources that may be allocated to it. If we could conceive of a situation in which we observed the performance of a given task relative to the attentional information processing demands set by a task performed concurrently, it would be possible to distinguish between these two alternatives. In the first instance, if the information processing demands of one of two concurrently performed tasks is held constant, and those of the other are selectively manipulated, the effect would only be reflected in the task being manipulated. In the second, however, since the performance of a given task is relative to the attentional resources available (or the difference between total and combined capacity demands), such independence between the tasks would not be observed, because if there were any spare capacity left in a well-motivated subject it would be allocated to increase the overall quality of performance.

In order to obtain empirical validation of either one of these two hypotheses, the following experiment was conducted:

METHOD

Subjects:

Six subjects took part in this experiment. All were male, right-handed, students in the University of Stirling, who were familiar with the visual and auditory tracking tasks. Four of the subjects had taken part in Experiment 2 and two of them were "best trackers" in Experiment 1. This experiment was run approximately eight weeks after Experiment 2 and approximately ten weeks after Experiment 1. As before, the subjects were paid £0.60/hr., and were told that the "best tracker" would receive a £2 bonus at the end of the experiment.

Apparatus and Materials

The same apparatus was used as in Experiments 1 and 2, but with two notable changes in the materials used. One involved a reduction in the tone frequency from 1Kz to 500 Hz. This was done, meeting Ss' requests, in order to make the auditory error display more 'pleasant' to track, although no improvement in tracking was observed when this change was made. This tone frequency change was made on the second, practice, session. The other change involved the forcing function signals and is described in detail below. This change was effected prior to the commencement of the experiment.

Forcing Functions

The forcing functions used were in every respect identical to those used in Experiments 1 and 2. The only change made concerned the relative amplitude of the component sinusoids. Component sinusoids below the cutoff frequency were ten times greater in amplitude than those in the high frequency shelf. The cutoff frequencies were once again .49, .86 and 1.84 rad/sec.

and the high frequency rectangular shelf extended, as before, to 4.79 rad/sec. All the signals involved, four to each bandwidth, were normalized to the 3.81 measured RMS deflection on the scope used in the previous experiments.

Procedure

Subjects took part in four 1-hour daily sessions, beginning on a Tuesday and going through to Friday of the same week. Then they returned the following Tuesday for another block of four, daily, 1-hour sessions. During the first block of four sessions the subjects tracked with zero order control dynamics. During the second block of sessions, the control dynamics were changed to first order. In order to acquaint the subjects with the various signal bandwidth combinations the first two sessions in each block of sessions were allocated to practice. On the following two days subjects performed nine different tracking conditions. The condition presentation order for the first day is given in Table 6.1. On the following (final) day, the presentation order was reversed. Subjects were given three trial replications of each condition each day after a one-trial practice run. Within-condition performance was usually stable, but if on any one trial a marked drop in performance was noted, rather than repeating the trial the practice trial tracking

TABLE 6.1

Condition presentation order. Experiment 3.

S	PRESENTATION ORDER								
1	(V1,A1)	(V2,A2)	(V3,A3)	(V1,A2)	(V1,A3)	(V2,A1)	(V2,A3)	(V3,A1)	(V3,A2)
2	(V2,A2)	(V3,A3)	(V1,A1)	(V1,A3)	(V2,A1)	(V1,A2)	(V3,A1)	(V3,A2)	(V2,A1)
3	(V2,A1)	(V1,A2)	(V1,A3)	(V3,A2)	(V2,A3)	(V3,A1)	(V3,A3)	(V2,A2)	(V1,A1)
4	(V2,A3)	(V3,A1)	(V3,A2)	(V2,A1)	(V1,A2)	(V1,A3)	(V1,A1)	(V2,A2)	(V3,A3)
5	(V3,A1)	(V1,A2)	(V2,A1)	(V1,A3)	(V2,A3)	(V3,A2)	(V2,A2)	(V3,A3)	(V1,A1)
6	(V2,A3)	(V3,A2)	(V1,A3)	(V3,A3)	(V1,A1)	(V2,A2)	(V2,A1)	(V1,A2)	(V3,A1)

Note: Visual input is represented by the letter V, auditory input by the letter A. The .49, .86, and 1.84 rad sec input signal bandwidths are represented by the numbers 1, 2, and 3, respectively. The (V2,A3) condition represents therefore, simultaneous visual and auditory tracking where the bandwidth of the visual input signal was .86 rad/sec and that of the auditory 1.84 rad/sec.

performance was used (but only if it was comparable to the other two trials). The subjects were unaware of this policy, and on only six occasions was it deemed advantageous to apply it. Subjects were given a short rest between conditions.

Presentation of the Data

The procedure followed in analysing the tracking data was the same for both proportional and rate control dynamics, though carried out separately.

Since the performance of a given visual or auditory tracking task was examined as a function of experimental manipulation of the information processing demands set by the other task performed concurrently, the performance of the "dependent" task will be represented in both figures and tables as a function of the manipulation carried out in the other "independent" task. Visual tracking performance, for example, will be considered and plotted as a function of the auditory tracking forcing function signal bandwidth. Thus, in presenting the data in such a way, it is possible to ascertain readily whether the performance of one tracking task depends in any obvious way on the information processing demands set by the other task. If the performance of the visual tracking task for .49, .86 and 1.84 rad/sec. input signals is independent of the auditory tracking task forcing function input bandwidth, the performance curves for each visual input signal bandwidth over the auditory input signal bandwidth should be more or less parallel, with auditory tracking task manipulations having no effect.

The forcing functions involved were not correlated. Moreover, since the comparisons of interest involved homogeneous and heterogeneous input conditions, the BOSAME tracking condition was dropped. The correlation coefficient relating the absolute visual and auditory tracking error signals was nevertheless examined in order to ascertain whether manipulating the heterogenity of the input signal bandwidth induced serial tracking performance or not.

Tracking NMSE, R_{max}, and τ measures were computed on the sampled data. The structure of each trial was in every sense the same as in Experiments 1 and 2. The data collection period began 20 secs after the beginning of each trial and lasted for [illegible]1.2 secs. The forcing function signals $i_v(t)$ and $i_a(t)$, the subject's control command signals $c_v(t)$ and $c_a(t)$ and the system output signals $m_v(t)$ and $m_a(t)$ were sampled from analog computer [illegible] terminals at a rate of 10 samples per second. In addition, the crosscorrelation function relating the subject's control command signals $c_v(t)$ and $c_a(t)$ were examined in order to determine the presence of crosscoupling between the loops noted by Van Lunteren (1977) in the context of dual,visual,compensatory tracking tasks.

RESULTS

Zero order and first order control visual and auditory tracking data were analyzed separately. The results for these two control dynamics conditions were nevertheless discussed together.

A. - Analysis of Zero Order Control Tracking Data

Analysis of Tracking NMSE measures

Visual Tracking

Average tracking NMSE values computed over trials and subjects are plotted for the .49, .86 and 1.84 rad/sec visual forcing function signal bandwidth as a function of auditory tracking forcing function signal bandwidth in Figure 6.1. Individual subject data is presented in Table 6.2. These data were submitted to an analysis of variance comprising two chief repeated-measures factors. One of these, with three levels, related to the .49, .86 and 1.84 rad/sec input signals. The other - also with three factors - related visual tracking performance in each of these

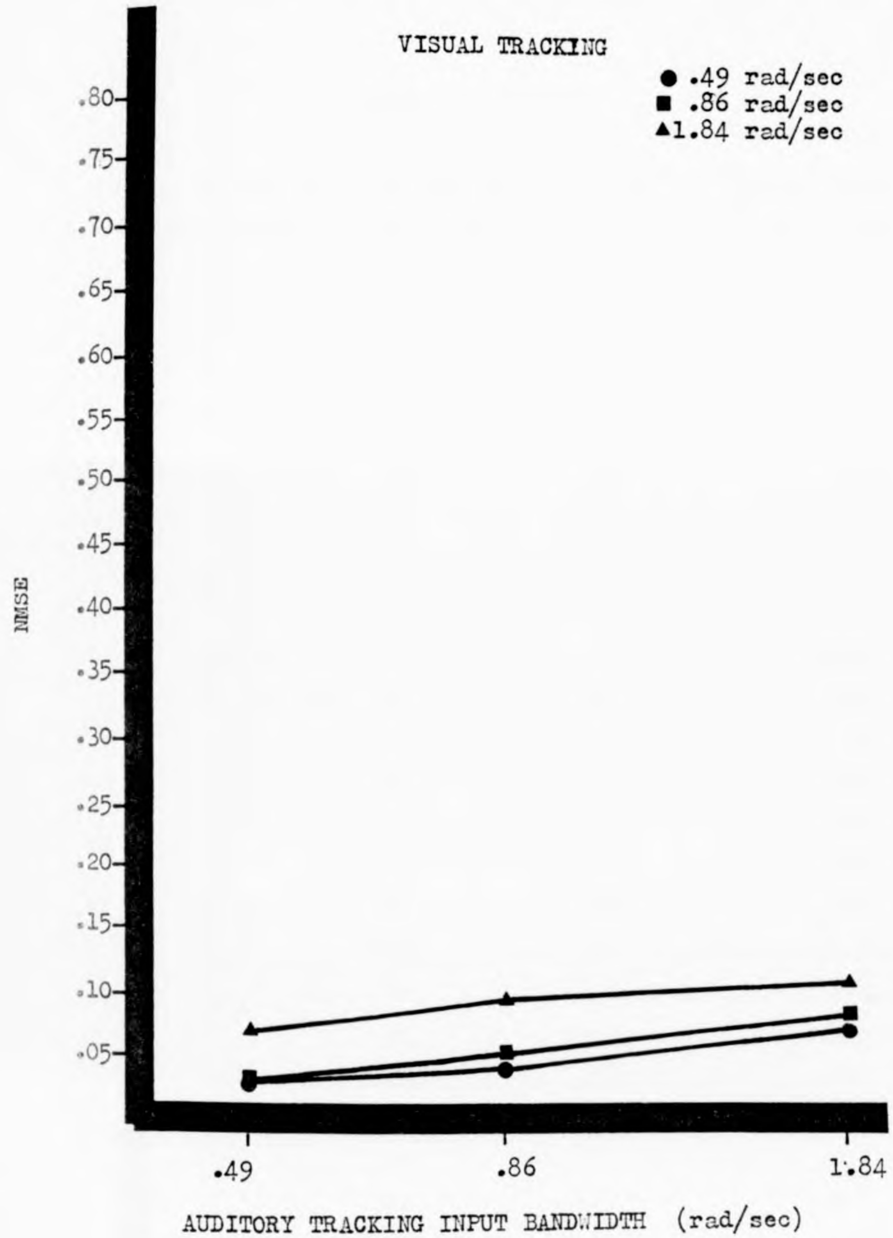

Fig. 6.1.-Visual tracking NMSE as a function of auditory tracking input bandwidth. Zero order control dynamics in each loop.

TABLE 6.2

Average visual tracking NMSE as a function of input bandwidth in both tracking loops. Zero order control dynamics. Experiment 3.

VISUAL INPUT (rad/sec)	S	AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1	.028	.050	.052
	2	.030	.056	.103
	3	.041	.093	.095
	4	.024	.040	.035
	5	.029	.032	.059
	6	.050	.053	.114
	$\bar{X}$=	.034	.054	.076
.86	1	.028	.040	.071
	2	.050	.047	.070
	3	.044	.052	.161
	4	.024	.023	.045
	5	.041	.064	.092
	6	.037	.100	.157
	$\bar{X}$=	.037	.054	.099
1.84	1	.053	.084	.082
	2	.080	.072	.097
	3	.100	.130	.157
	4	.053	.069	.057
	5	.063	.090	.102
	6	.097	.133	.155
	$\bar{X}$=	.074	.096	.108

Average of 6 trials per cell.

TABLE 6.3

Summary ANOVA table of average normalized mean-squared visual tracking error in Experiment 3. Zero order control dynamics.

SOURCE	DF	SS	MS	F	PROB
Subjects	5	0.025			
Bandwidth {V}	2	0.014	0.007	30.0803	0.0001
EW1B	10	0.002	0.001		
Bandwidth {A}	2	0.019	0.010	16.3861	0.0000
EW2B	10	0.006	0.001		
{V x A}	4	0.002	0.001	2.0425	0.1261
EW12B	20	0.005	0.001		
[illegible]	48	0.049			
[illegible]Q/N=	0.2680	N=	54	SST=	0.0736

signal bandwidths to the .49, .86 and 1.84 rad/sec auditory input signal bandwidths. A summary ANOVA table appears in Table 6.3.

Both main effects were highly significant. The visual bandwidth main effect is represented in Table 6.3, as bandwidth {V}, and the auditory forcing condition bandwidth manipulation is represented as main effect bandwidth {A}. The interaction relating these two factors was not. The non-significant interaction indicates that although the auditory tracking forcing function bandwidth manipulation may well have effected significant changes in visual tracking performance, the effects were affecting visual tracking performance quite independently of the visual input signal bandwidth. If we now turn to Figure 6.1, we note the following pattern of results. Visual tracking NMSE increased significantly with visual forcing function signal bandwidth. NMSE values for the .49, .86 and 1.84 rad/sec visual input signals were .055, .064 and .093 respectively. This result replicates that obtained in Experiment 1, where visual tracking NMSE was found to increase with forcing function bandwidth.

Visual tracking NMSE was also found to vary significantly with the bandwidth of the auditory tracking forcing function input signal. Consider first visual tracking

NMSE of the .49 rad/sec input signal. These values are represented in Figure 6.1 as the curve nearest the abscissa on the graph. This curve is not perfectly flat and can be seen to increase gently upward. Visual NMSE values increase with auditory input signal bandwidth ($p < .01$) from .034 to .054, and to .076, simply because the forcing function in the auditory tracking loop was raised from .49 to .86 and to 1.84 rad/sec. We note, of course, that the lowest point on the graph representing the average NMSE value for the .49 rad/sec visual input, when the .49 rad/sec input was tracked simultaneously in the auditory loop, corresponds to a homogeneous input condition. By similar observation we can locate, therefore, on the .86 rad/sec curve the center point as representing tracking NMSE for homogeneous visual and auditory tracking forcing function input signals. Likewise, the right uppermost triangle in the 1.84 rad/sec visual tracking NMSE curve represents the average visual tracking NMSE value for 1.84 rad/sec homogeneous visual and auditory forcing function input signals. We are now in a position to scan the curves in either direction, with these points as a reference, to appreciate how performance measures along a given curve increase or decrease with corresponding variation of the auditory input signal bandwidth. Increases in NMSE relative to the homogeneous control condition indicate decrements in visual tracking performance attributable directly to interference with the auditory tracking task. Relative decreases along the curve indicate, however, relative improvements in the performance of the visual tracking task with corresponding reduction in the auditory forcing function signal bandwidth. For all the curves represented in Figure 6.1, the contrasts relating the highest and lowest points in each curve were highly significant ($p < .01$). If we turn to Table 6.2, we observe this general pattern of results to be well distributed across subjects. Overall, visual tracking NMSE was found to increase more or less in linear, monotonic fashion with log frequency increases in the auditory forcing function signal bandwidth, from .048, to .068 and to .095, when the auditory input signal bandwidth was raised from .49, to .86 and to 1.84 rad/sec.

Auditory Tracking

The results for the auditory tracking tasks not only corroborate those obtained in the visual tracking conditions but are even more dramatic. Mean NMSE values are presented graphically in Figure 6.2, and in tabular form for each subject individually in Table 6.4.

A two-way within-subject design analysis of variance was conducted on the mean NMSE values, averaged over

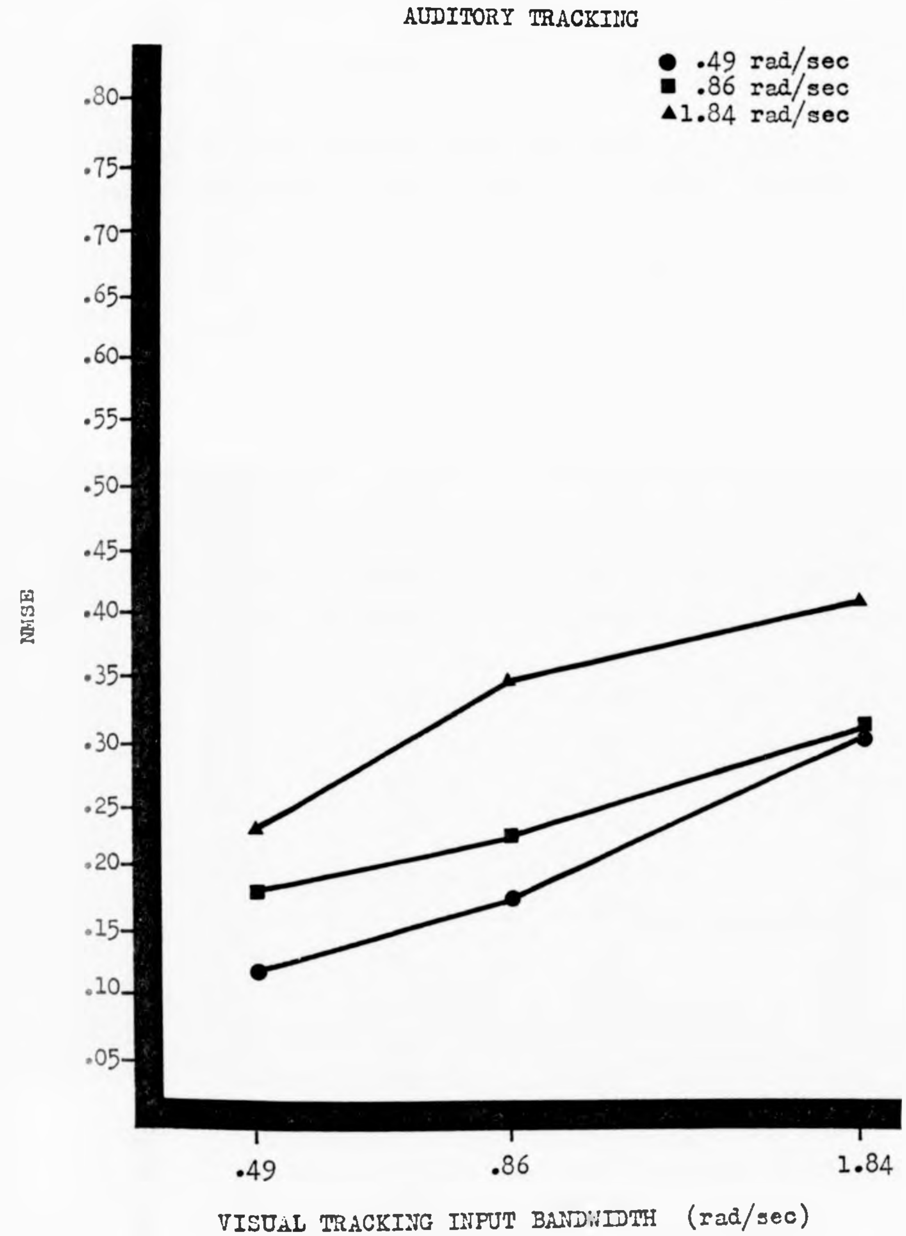

Fig. 6.2.-Auditory tracking NMSE as a function of visual tracking input bandwidth. Zero order control dynamics in each loop.

TABLE 6.4

Average auditory tracking NMSE as a function of input bandwidth in both control loops. Zero order control dynamics.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	.166	.224	.203
	2	.113	.256	.280
	3	.083	.141	.178
	4	.170	.174	.545
	5	.178	.140	.302
	6	.098	.133	.319
	$\bar{X}$=	.135	.178	.305
.86	1	.144	.227	.179
	2	.225	.300	.402
	3	.108	.171	.218
	4	.296	.233	.308
	5	.144	.155	.381
	6	.192	.240	.347
	$\bar{X}$=	.185	.222	.306
1.84	1	.236	.237	.402
	2	.275	.423	.482
	3	.196	.218	.264
	4	.238	.351	.390
	5	.216	.346	.400
	6	.224	.503	.516
	$\bar{X}$=	.231	.346	.409

TABLE 6.5

Summary ANOVA table on average normalized mean-squared auditory tracking error in Experiment 3.
Zero order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	0.116			
Bandwidth {A}	2	0.147	0.073	17.1947	0.0007
EW1B	10	0.043	0.004		
Bandwidth {V}	2	0.222	0.111	26.7250	0.0001
EW2B	10	0.042	0.004		
{A x V}	4	0.016	0.004	0.9376	0.5363
EW12B	20	0.084	0.004		
W	48	0.553			
T[illegible]/N=	3.5728	N=	54	SST=	0.6693

trial replications. One factor represented the auditory input bandwidth variable with three levels. The other represented the auditory input bandwidth variable also with three factors. A summary ANOVA table is presented in Table 6.5. As is evident from perusal of the ANOVA table, both the visual input bandwidth and the auditory bandwidth main effects were highly significant, while their interaction was not. Average auditory tracking NMSE increased monotonically with corresponding increases in auditory tracking input signal bandwidth from .206, to .237, to .329. In addition, average auditory tracking NMSE was also found to be tied to visual tracking input bandwidth. NMSE increases from .183, to .248, to .340 were found to accompany corresponding increases in visual input bandwidth from .49, to .86, to 1.84 rad/sec. This effect was observed even when the auditory tracking input bandwidth was only .49 rad/sec ($p<.001$).

Tracking Linearity R_{max} Measure

Visual Tracking

Average tracking linearity measures R_{max} over trial replications were computed individually for each visual forcing function bandwidth, for each level of the auditory bandwidth variable and for each subject. These means were then

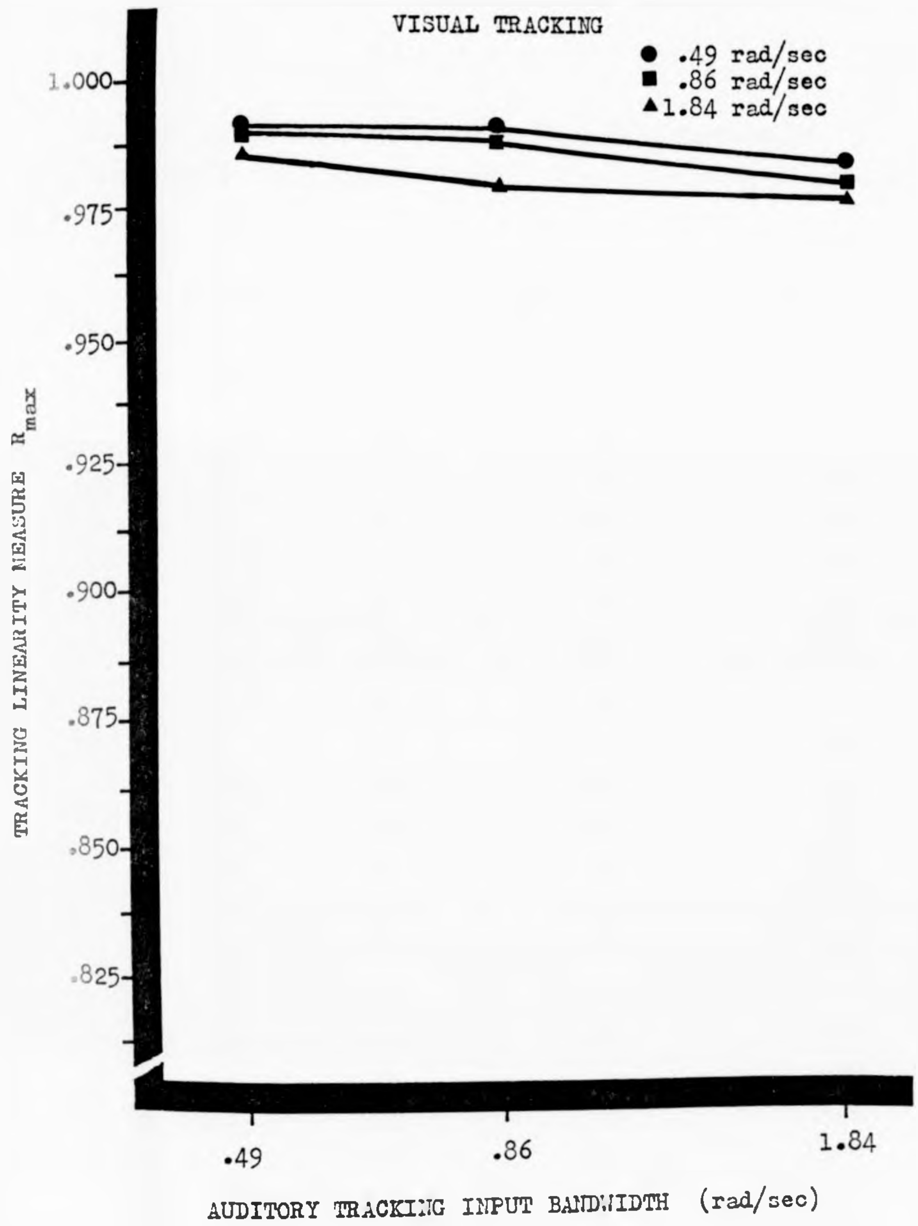

Fig.6.3.- Visual tracking linearity measure R_{max} as a function of input bandwidth in auditory loop. Zero order control dynamics in each loop.

TABLE 6.6

Average visual tracking linearity, R_{max}, as a function of input bandwidth in both control loops. Zero order control dynamics. Experiment 3.

VISUAL INPUT (rad/sec)	S	AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1	.993	.990	.985
	2	.995	.992	.977
	3	.994	.988	.980
	4	.994	.993	.992
	5	.994	.996	.991
	6	.990	.992	.982
	$\bar{X}$=	.993	.992	.985
.86	1	.994	.991	.986
	2	.991	.991	.987
	3	.985	.991	.974
	4	.994	.994	.993
	5	.992	.992	.990
	6	.985	.976	.950
	$\bar{X}$=	.990	.989	.980
1.84	1	.987	.984	.977
	2	.986	.987	.985
	3	.978	.974	.968
	4	.991	.979	.986
	5	.991	.987	.989
	6	.980	.968	.963
	$\bar{X}$=	.986	.980	.978

Average of 6 trials per cell.

TABLE 6.7

Summary ANOVA table of average visual tracking linearity, R_{max}, measures in Experiment 3. Zero order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	0.002			
Bandwidth {V}	2	0.001	0.001	6.6788	0.0144
EW1B	10	0.001	0.001		
Bandwidth {A}	2	0.001	0.001	9.0094	0.0059
EW2B	10	0.001	0.001		
{V x A}	4	0.001	0.001	1.4835	0.2441
EW12B	20	0.001	0.001		
W	48	0.003			
TSQ/N=	52.4789	N=	54	SST=	0.0044

submitted to a two-way analysis of variance with two repeated-measures factors: (1) visual tracking input bandwidth and (2) auditory bandwidth. Individual subject data for each treatment variable is presented in Table 6.6. Mean R_{max} values, computed over subjects, are presented graphically in Figure 6.3. A summary ANOVA table is presented in Table 6.7.

Increases in visual input-bandwidth significantly reduced visual tracking linearity R_{max}. For the .49, .86 and 1.84 rad/sec inputs the observed decrements in R_{max} were .990, .987 and .981 respectively. Besides varying with input bandwidth, visual tracking linearity was also found to depend on the auditory tracking input bandwidth. Tracking linearity decreased from what represents remarkably linear tracking behavior, an average value of .990 for the .49 rad/sec auditory input signal bandwidth, down to .981; a small but highly significant difference. Significant decrements in visual tracking linearity were also found to accompany the increases in auditory tracking input bandwidth for each of the other (.86 and 1.84 rad/sec) visual forcing function signal bandwidths.

Auditory Tracking

The R_{max} values in the auditory tracking

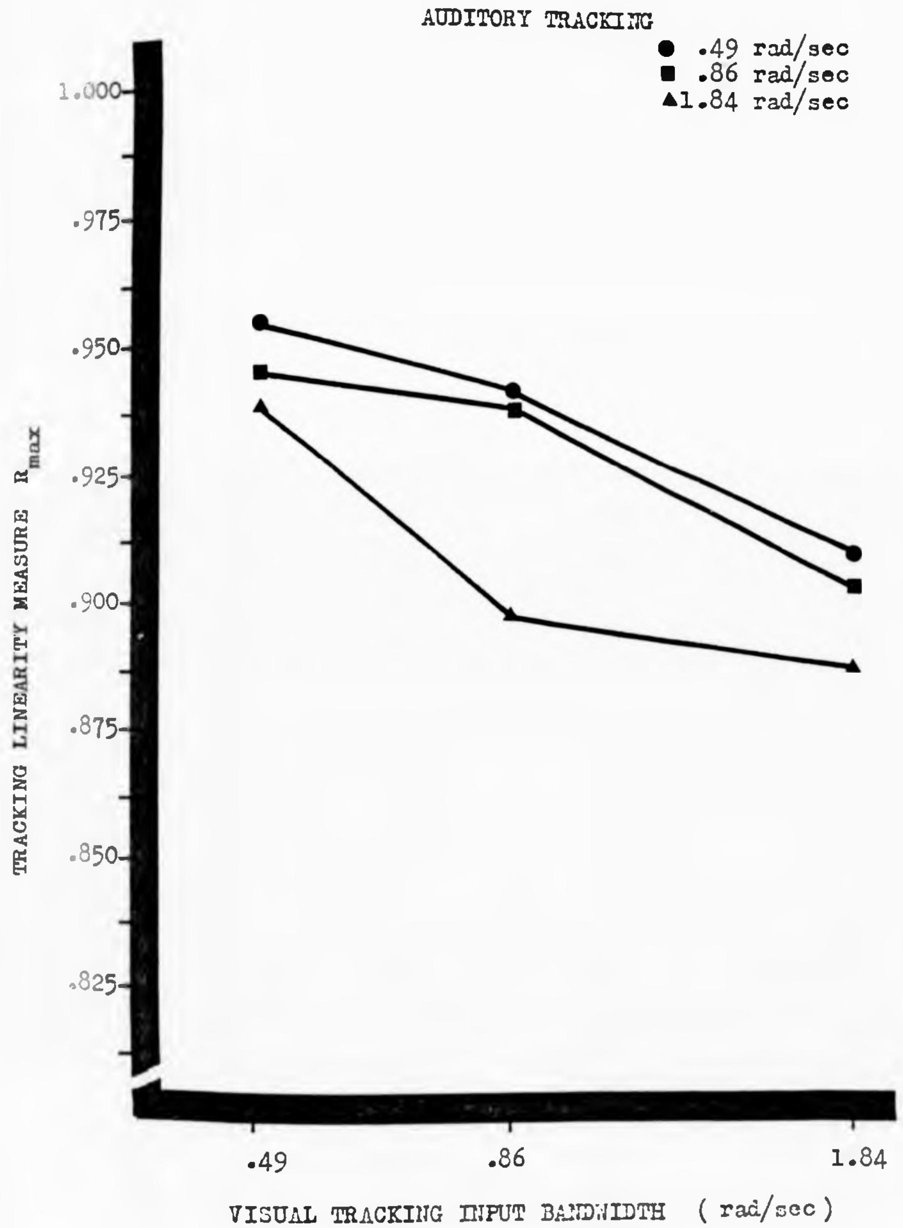

Fig. 6.4.- Auditory tracking linearity measure R_{max} as a function of input bandwidth in the visual tracking loop. Zero order control dynamics in each loop.

TABLE 6.8

Average auditory tracking linearity, R_{max}, as a function of input bandwidth in both control loops. Zero order control. Experiment 3.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	.937	.934	.949
	2	.962	.909	.923
	3	.980	.970	.961
	4	.950	.940	.790
	5	.934	.967	.930
	6	.967	.960	.884
	$\bar{X}$=	.955	.947	.906
.86	1	.951	.935	.945
	2	.949	.902	.882
	3	.976	.961	.952
	4	.872	.931	.887
	5	.970	.970	.983
	6	.959	.937	.913
	$\bar{X}$=	.946	.939	.912
1.84	1	.935	.927	.872
	2	.930	.856	.872
	3	.954	.963	.947
	4	.932	.868	.862
	5	.941	.938	.943
	6	.941	.834	.845
	$\bar{X}$=	.938	.898	.890

Average of 6 trials per cell.

TABLE 6.9

Summary ANOVA table of average auditory tracking linearity, R_{max} - measures in Experiment 3. Zero order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	0.032			
Bandwidth {A}	2	0.009	0.005	7.4512	0.0105
EW1B	10	0.006	0.001		
Bandwidth {V}	2	0.014	0.007	5.6593	0.0226
EW2B	10	0.012	0.001		
{A x V}	4	0.004	0.001	1.3427	0.2886
EW12B	20	0.015	0.001		
W	48	0.060			
[illegible]/N=	46.4483	N= 54		SST=	0.0922

conditions were slightly more variable and lower, but they nevertheless paralleled those for visual tracking. Mean auditory tracking R_{max} values for each input bandwidth averaged over subjects, plotted as a function of visual input bandwidth, are presented in Figure 6.4. Individual subject data are presented in Table 6.8. Mean R_{max} values for the six subjects in each auditory input signal were submitted to a two-way analysis of variance with repeated measures on both factors: an auditory tracking input bandwidth factor with three levels corresponding to the .49, .86 and 1.84 rad/sec signals and a visual input bandwidth variable. The two main effects were statistically significant, and the two-way interaction was not. Auditory tracking linearity was found to depend on auditory tracking input bandwidth with values of .936 for the .49 rad/sec input, .938 for the 1.86 rad/sec input and .909 for the 1.84 rad/sec input. Auditory tracking linearity was also found to depend on the input signal bandwidth of the visual tracking task concurrently performed. This effect was significant for both the .49 and the 1.84 rad/sec auditory inputs but not for the .86 rad/sec input. Whether the fact that the bandwidth of the signals tracked by the subjects in Experiment 2 was also .86 rad/sec has any bearing on this is not certain. A very small hint that tracking linearity might have been increased with homogeneous .86 rad/sec inputs in the visual tracking R_{max} graph presented in Figure 6.4 is given in support of the notion that the subject's previous experience in tracking a .86 rad/sec signal with zero order control dynamics must have proved to be the source of a minor carry-over effect, but only in general experience at tracking .86 rad/sec inputs. This must have been so because each forcing function waveform was different from experiment to experiment. The possibility of selective training to one particular bandwidth is not dismissed, however, and remains an interesting possibility. If so, it would appear that such a carry-over effect served to reduce tracking remnant.

Average Tracking Response Delay τ.

Visual Tracking

Average response delay τ measures were computed over trial replications for each subject individually and for each visual tracking input bandwidth separately. These values are presented in tabular form in Table 6.10. These values were averaged over subjects and are plotted as a function of auditory tracking input bandwidth in Figure 6.5. Individual subject mean values for each visual input signal bandwidth were submitted to a two-way within-subject design analysis of variance. There were two chief factors: a visual input signal bandwidth variable with

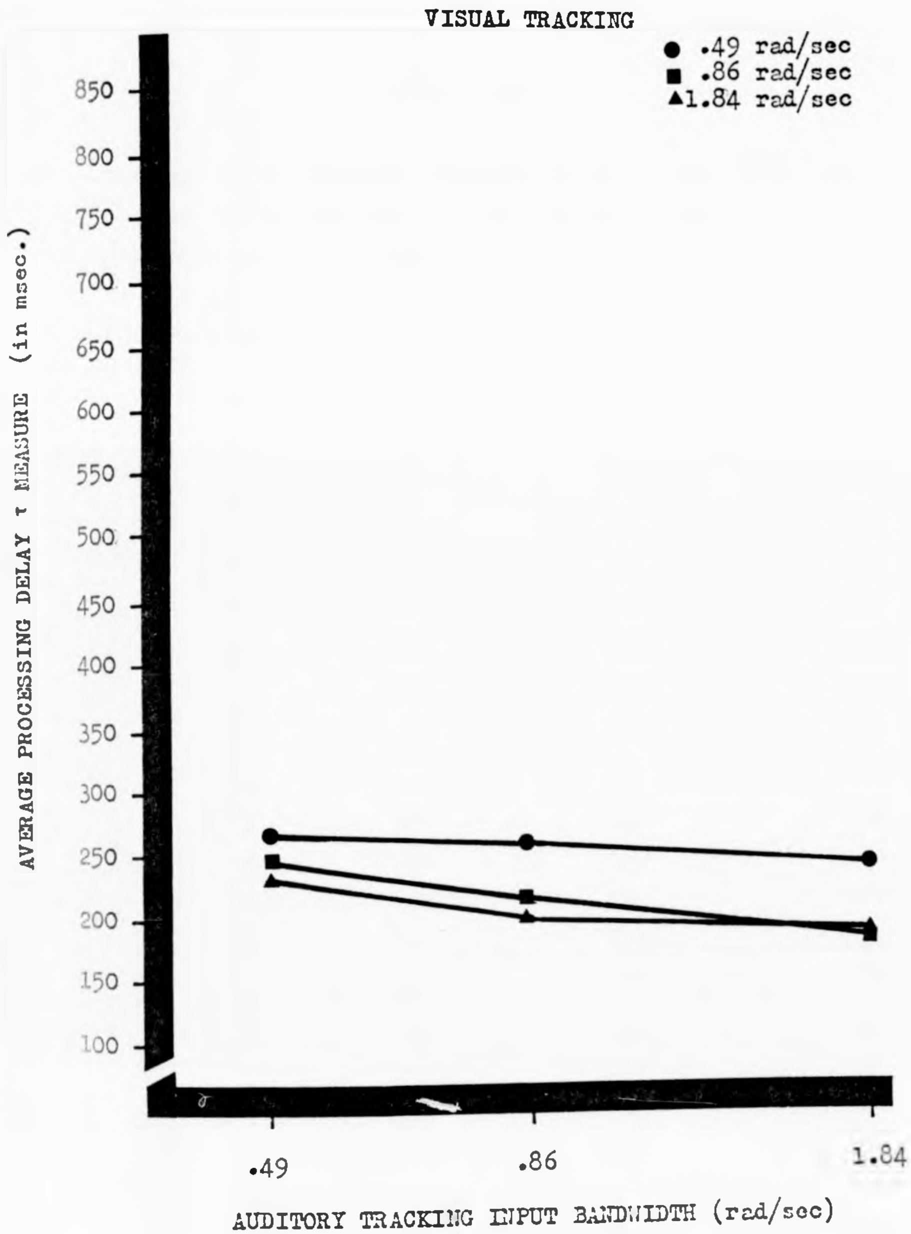

Fig. 6.5.-Average processing delay τ measure as a function of input bandwidth in the auditory tracking loop. Zero order control dynamics in each loop.

TABLE 6.10

Average visual tracking response delay, τ (in msec), as a function of input bandwidth in both control loops. Zero order control. Experiment 3.

VISUAL INPUT (rad/sec)	S		AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1		225	200	175
	2		250	250	250
	3		350	350	300
	4		175	250	150
	5		250	225	300
	6		325	275	275
		$\bar{X}$=	263	258	242
.86	1		200	200	150
	2		275	200	200
	3		325	200	225
	4		150	100	100
	5		250	300	200
	6		250	300	250
		$\bar{X}$=	242	217	188
1.84	1		200	200	150
	2		250	200	200
	3		325	250	250
	4		150	150	100
	5		225	200	200
	6		250	225	250
		$\bar{X}$=	233	204	192

Average of 6 trials per cell.

TABLE 6.11

Summary ANOVA Table of average visual tracking response delay, τ, measures in Experiment 3. Zero order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	117326.500			
Bandwidth {V}	2	21111.000	10555.500	11.0145	0.0031
EW1B	10	9583.250	958.325		
Bandwidth {A}	2	13611.000	6805.500	7.4241	0.0107
EW2B	10	9166.750	916.675		
{V x A}	4	2153.000	538.250	0.5364	0.7130
EW12B	20	20069.250	1003.463		
W	48	75694.250			

TSQ/N= 2767604.2500 N= 54 SST= 193020.7500

TABLE 6.11

Summary ANOVA Table of average visual tracking response delay, τ, measures in Experiment 3. Zero order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	117326.500			
Bandwidth {V}	2	21111.000	10555.500	11.0145	0.0031
EW1B	10	9583.250	958.325		
Bandwidth {A}	2	13611.000	6805.500	7.4241	0.0107
EW2B	10	9166.750	916.675		
{V x A}	4	2153.000	538.250	0.5364	0.7130
EW12B	20	20069.250	1003.463		
W	48	75694.250			

TSQ/N= 2767604.2500 N= 54 SST= 193020.7500

three levels corresponding to the .49, .86 and 1.84 rad/sec signals and an auditory input signal bandwidth factor with three levels corresponding to the .49, .86 and 1.84 rad/sec auditory forcing functions. Summary ANOVA table is presented in Table 6.11.

The two main effects were statistically significant, but, once more, the two-way visual input bandwidth by auditory input bandwidth interaction was not. Increasing the visual tracking input signal bandwidth led to a reduction in mean response delay from 254 msec for the .49 rad/sec input to 215 for the .86 rad/sec input, and a further 5 msec reduction to 210 msec for the 1.84 rad/sec input. Though small, the effect was highly significant. Average tracking response delay measures were also found to decrease monotonically with auditory tracking input signal bandwidth, in 20 msec steps, from 246 msecs for the .49 rad/sec input to 226 msec for the .86 rad/sec input, and to 206 for the 1.84 rad/sec input signal. This reduction in visual tracking response delay with auditory input signal bandwidth was only evident for the .86 and 1.84 rad/sec visual input signals ($p < .05$).

Auditory Tracking

The results obtained in the visual tracking

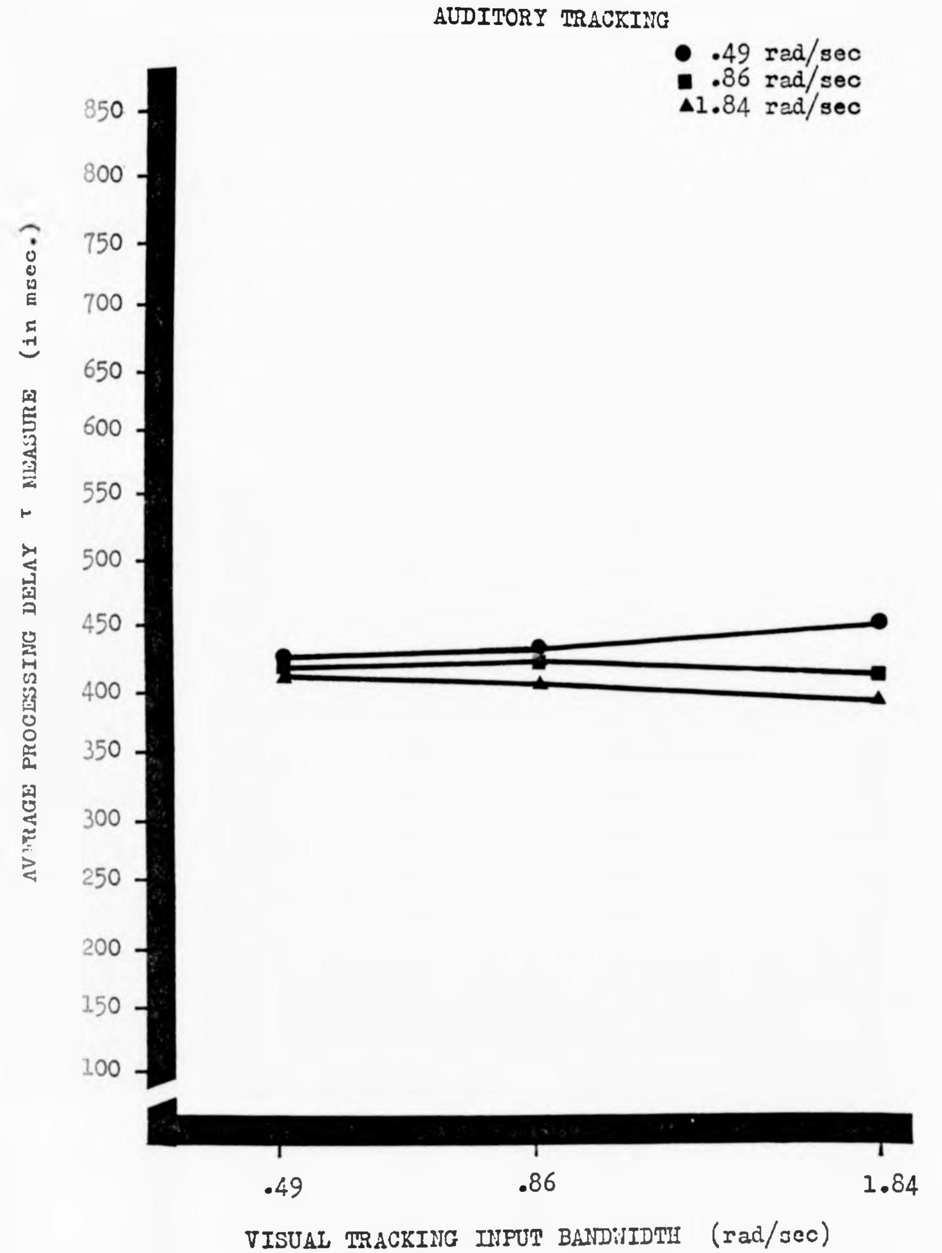

Fig. 6.6.-Average processing delay τ measure as a function of input bandwidth in the visual tracking loop. Zero order control dynamics in each loop.

TABLE 6.12

Average auditory tracking response delay, τ (in msec), as a function of input bandwidth in both control loops. Zero order control dynamics. Experiment 3.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	400	450	350
	2	450	475	400
	3	400	425	400
	4	725	400	700
	5	525	425	500
	6	400	400	350
	$\bar{X}$=	483	429	450
.86	1	325	400	250
	2	575	475	575
	3	375	400	350
	4	375	400	350
	5	425	400	400
	6	450	475	550
	$\bar{X}$=	421	425	413
1.84	1	400	300	375
	2	450	475	450
	3	400	400	375
	4	400	300	300
	5	425	500	450
	6	425	575	525
	$\bar{X}$=	417	425	326

Average of 6 trials per cell.

TABLE 6.13

Summary ANOVA table of average auditory tracking response delay, τ, measures in Experiment 3. Zero order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	91944.000			
Bandwidth {A}	2	15069.000	7534.500	0.4175	0.6737
EW1B	10	180487.000	18048.699		
Bandwidth {V}	2	2569.000	1284.500	0.3274	0.7315
EW2B	10	39237.000	3923.700		
{A x V}	4	7362.000	1840.500	0.4310	0.7864
EW12B	20	85415.000	4270.750		
W	48	330139.000			

SSQ/N= 10010417.0000 N= 54 SST= 422083.0000 conditions for average tracking response delay τ measures were not replicated when tracking involved the auditory modality.

Mean τ values for each subject and for each auditory tracking input signal bandwidth were submitted to a two-way analysis of variance with repeated measures on both factors. Individual subject data are presented in Table 6.12 and average tracking delay τ measures averaged over subjects are plotted as a function of visual forcing function bandwidth in Figure 6.6. Summary ANOVA table is presented in Table 6.13. It is evident from examination of Table 6.12 that none of the main effects nor the two-way interaction was statistically significant.

Correlation between the Absolute Tracking Error Signals

Average correlation coefficients between the absolute visual and auditory tracking error signals, computed over trials, are presented for each subject in each condition in Table 6.14. Examination of Table 6.14 reveals very low overall correlation between the absolute tracking error signals. Any value exceeding $\pm$.087 is significant at the .05 level. Although some significant values are present, it is very difficult to draw any meaningful relationships because they vary most inconsistently between subjects. We note no consistent negative correlations

TABLE 6.14

Average correlation values, r, between the absolute tracking error signals in the homogeneous and heterogeneous inputs conditions in Experiment 3. Zero order control dynamics.

VISUAL INPUT (rad/sec)	S	AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1	.016	.090	.085
	2	.047	-.002	.023
	3	-.088	.022	-.204
	4	.083	.048	.056
	5	.021	-.027	-.012
	6	.072	-.091	-.013
	$\bar{X}$=	.025 (.06)	.007 (.06)	-.011 (.10)
.86	1	.016	.104	.052
	2	.051	.138	.022
	3	-.030	.061	.039
	4	.081	-.025	.015
	5	-.050	-.085	.051
	6	.049	.032	.025
	$\bar{X}$=	.014 (.05)	.038 (.08)	.034 (.02)
1.84	1	.059	.013	-.023
	2	-.019	-.023	.028
	3	.070	.087	.021
	4	-.095	-.007	.049
	5	-.075	-.113	-.011
	6	.028	.131	.005
	$\bar{X}$=	-.005 (.07)	.028 (.09)	.012 (.03)

erage of 6 trials in each cell. Values within parentheses resent standard deviation.

as the .49, .86 and 1.84 rad/sec input conditions became less homogeneous with changes in either the visual or the auditory forcing function bandwidth. There is no evidence, therefore, of any tendency for the absolute tracking error signals to become linearly related as (1) the bandwidth of the forcing function was selectively increased homogeneously between the tracking loops or (2) heterogeneously between the loops. It would appear, therefore, that in dealing with the input signals subjects were operating to reduce perceived tracking error in parallel.

Linear Correlation between the Subject's Control Command Signals $c_v(t)$ and $c_a(t)$: An Analysis of Crosscoupling between the Loops

If the performance of one of two concurrently performed tracking tasks is found to decrease as the information processing demands of the other task are increased, it may still not be possible to ascribe such a time-sharing effect to an attentional limitation. If it were to be the case that some of the control command responses directed at the varying task were "spilling" over to the task under examination, it would serve to explain the corresponding variations in the performance of that task. Improper response differentiation between the hands would be represented as an internal crosscoupling in the human operator that may, or may not, have anything to do with an actual optimal allocation of attentional capacity, differentiated or otherwise. In order to determine whether such linear cross-coupling between the loops as that noted by Van Lunteren (1977) was also operative in this experiment, the subject's response, control command, signals $c_v(t)$ and $c_a(t)$ were correlated. If linear crosscoupling between the loops was causing linear variation in bandwidth for both tracking tasks, even though only one of these was being manipulated, then it is conceivable that a linear correlation between the $c_v(t)$ and $c_a(t)$ signals would exist. Conversely, if the time-sharing decrements in performance observed for both tasks performed concurrently arose as a natural consequence of limitations in central attentional resources, then there is no obvious reason to believe that any correlation between the movements of the two hands should exist, since, after all, the forcing function input signals were not correlated in any obvious way.

The correlation coefficient between the $c_v(t)$ and $c_a(t)$ signals was computed on each trial separately. Individual subject data in each homogeneous/heterogeneous inputs condition are presented in Table 6.15. We note once more that a correlation coefficient value exceeding $\pm.087$ is significant at the .05 level. Examination of the table does not reveal any obvious pattern. Nevertheless, it is noteworthy that, on occasion, a significant but

TABLE 6.15

Average crosscorrelation peak values between the operator's control command movement signals $c_v(t)$ and $c_a(t)$ with homogeneous and heterogeneous inputs. Zero order control dynamics.

VISUAL INPUT (rad/sec)	S	AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1	.043	.035	.022
	2	-.003	.037	.134
	3	.002	.038	.015
	4	-.098	-.062	.092
	5	-.050	.009	.062
	6	.005	.042	.142
	$\bar{X}$=	-.024	.020	.078
.86	1	.053	.017	.090
	2	.124	.064	.085
	3	.109	.049	-.013
	4	.094	-.005	.012
	5	0.83	.050	.071
	6	.074	.092	.070
	$\bar{X}$=	.090	.045	.053
1.84	1	.104	.114	.121
	2	.028	.084	.027
	3	.135	.093	.081
	4	.020	-.058	-.029
	5	.091	.064	.091
	6	.099	.079	.147
	$\bar{X}$=	.080	.063	.073

Average of 6 trials in each cell.

very low correlation between the signals was registered. These values were not consistent, however, either between subjects in the various conditions or within subjects across conditions, whereas examination of the NMSE, R_{max} and τ data tables suggests the observed effects to be rather uniform across subjects in all conditions.

A. Analysis of First Order Control Data

Normalized Mean-Squared Tracking Error

Visual Tracking

Mean visual tracking NMSE values, averaged over trials, for each visual input signal bandwidth and for each subject separately, were submitted to a two-way analysis of variance with repeated measures on both factors. There were two chief factors: (1) visual forcing function signal bandwidth, with three levels, and (2) auditory forcing function signal bandwidth, also with three levels. Mean NMSE values averaged over subjects are plotted as a function of auditory tracking input bandwidth in figure 6.7. Individual subject data are presented in Table 6.16. A Summary ANOVA table is presented in Table 6.17.

The two main effects were highly significant, and

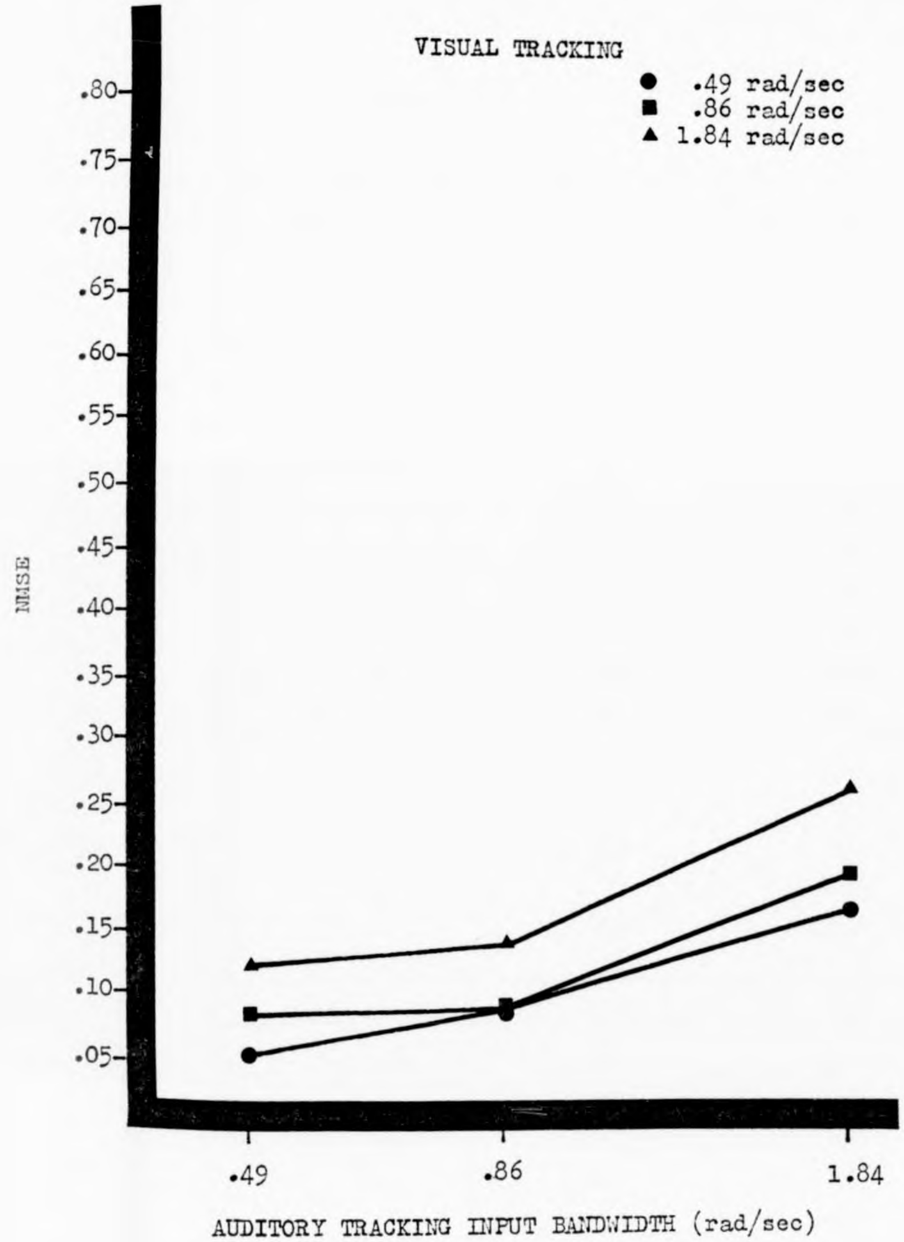

Fig. 6.7.- Visual tracking NMSE as a function of auditory tracking input bandwidth. First order control dynamics in each loop.

TABLE 6.16

Average visual tracking NMSE as a function of input bandwidth in both control loops. First order control dynamics. Experiment 3.

VISUAL INPUT (rad/sec)	S	AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1	.054	.042	.130
	2	.046	.053	.084
	3	.116	.233	.263
	4	.030	.101	.228
	5	.044	.059	.148
	6	.047	.072	.173
	$\bar{X}$=	.056	.093	.171
.86	1	.048	.067	.071
	2	.086	.087	.128
	3	.163	.128	.449
	4	.045	.103	.293
	5	.094	.079	.128
	6	.073	.074	.142
	$\bar{X}$=	.085	.090	.202
1.84	1	.064	.084	.143
	2	.127	.179	.167
	3	.280	.257	.428
	4	.061	.060	.501
	5	.113	.118	.170
	6	.120	.157	.183
	$\bar{X}$=	.128	.143	.265

Average of 6 trials per cell.

TABLE 6.17

Summary ANOVA table of average visual tracking NMSE in Experiment 3. First order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	0.187			
Bandwidth {V}	2	0.050	0.025	24.8800	0.0002
EW1B	10	0.010	0.001		
Bandwidth {A}	2	0.158	0.079	8.6632	0.0067
EW2B	10	0.091	0.009		
{V x A}	4	0.004	0.001	0.3550	0.8384
EW12B	20	0.056	0.003		
W	48	0.369			
[illegible]Q/N=	1.0122	N=	54	SST=	0.5564

the two-way interaction was not. A pattern of results qualitatively similar to those observed when the controlled element dynamics were zero order was found. Increasing the visual input bandwidth from .49 rad/sec to .86 and to 1.84 rad/sec produced corresponding average increases in tracking NMSE from .107 to .125 to .178. Average visual tracking NMSE was also found to vary with the bandwidth of the auditory forcing function input signal, from .090 for the .49 rad/sec input signal to .109 for the .86 rad/sec signal and to .213 for the 1.84 rad/sec signal. It appeared once more as if the manipulation of the auditory input signal bandwidth was effecting corresponding changes in visual tracking performance, the effects being considerably more marked than those observed for zero order controlled element dynamics.

Auditory Tracking

Average auditory tracking NMSE values, computed over trial replications, for each auditory tracking input signal and for each subject separately, were submitted to a two-way analysis of variance. Once more, a treatments-by-treatments-by-subjects design was used. Mean NMSE values averaged over subjects are plotted for each .49, .86 and 1.84 rad/sec auditory tracking signal separately, as a function of the visual tracking input signal bandwidth in Figure 6.8. Individual subject data is

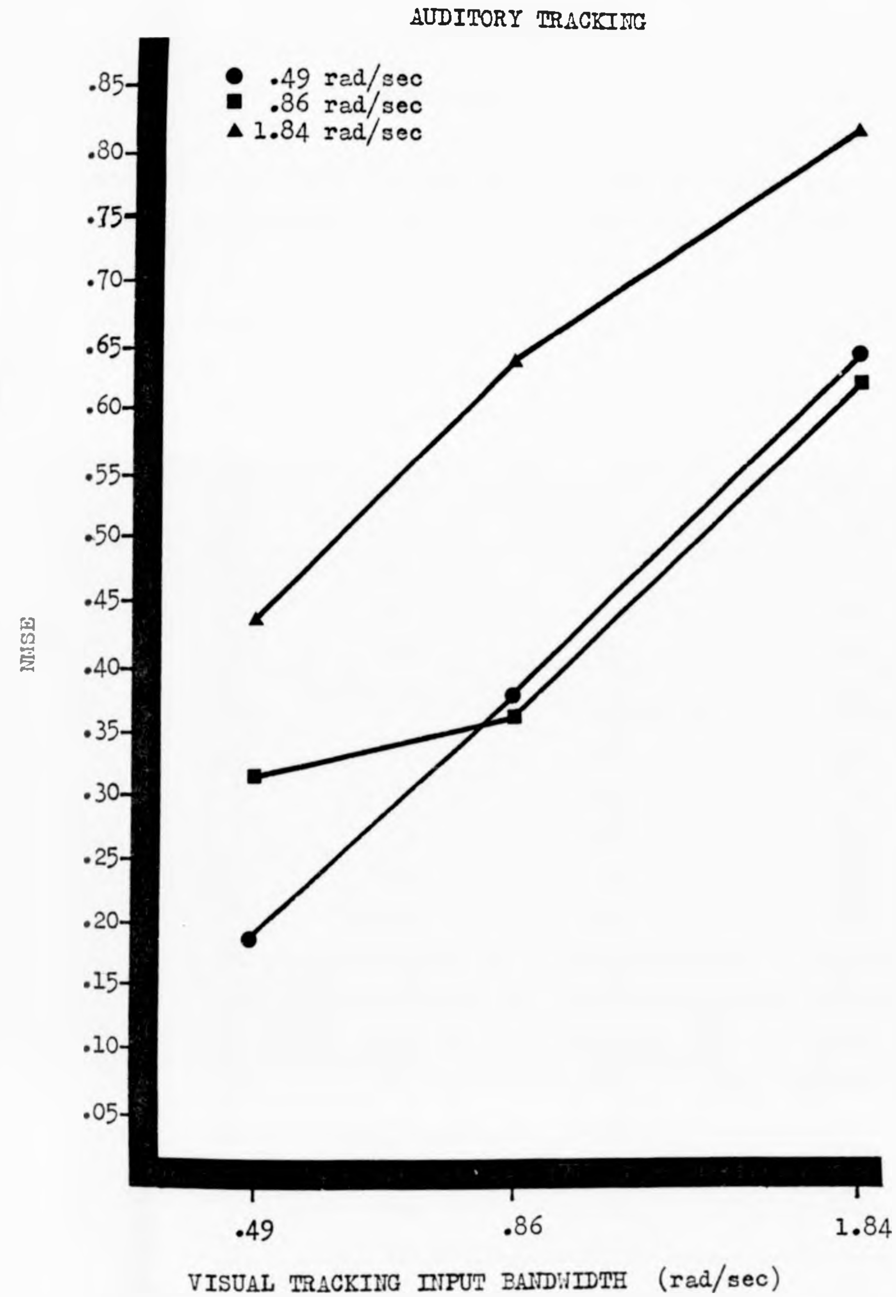

Fig. 6.8.- Auditory tracking NMSE as a function of visual tracking input bandwidth. First order control dynamics in each loop.

TABLE 6.18

Average auditory tracking NMSE as a function of input bandwidth in both control loops. First order control dynamics. Experiment 3.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	.152	.244	.409
	2	.280	.502	.725
	3	.180	.565	.499
	4	.204	.451	.793
	5	.161	.222	.442
	6	.165	.277	.998
	X̄=	.190	.377	.644
.86	1	.152	.306	.384
	2	.492	.595	.771
	3	.388	.285	.745
	4	.262	.424	.557
	5	.287	.302	.764
	6	.317	.259	.521
	X̄=	.316	.362	.624
1.84	1	.346	.393	.726
	2	.576	.623	.897
	3	.547	.646	.701
	4	.641	.642	.906
	5	.448	.590	.661
	6	.357	.971	1.048
	X̄=	.486	.644	.823

Average of 6 trials per cell.

TABLE 6.19

Summary ANOVA table of average auditory tracking NMSE, in Experiment 3. First order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	0.394			
Bandwidth {A}	2	0.655	0.327	20.8381	0.0003
EW1B	10	0.157	0.016		
Bandwidth {V}	2	1.241	0.620	64.0001	0.0001
EW2B	10	0.097	0.010		
{A x V}	4	0.056	0.014	0.7397	0.5781
EW12B	20	0.379	0.019		
W	48	2.585			

SSQ/N= 13.2998 N= 54 SST= 2.9796

presented in Table 6.18. A summary ANOVA table is presented Table 6.19.

The results were once again straightforward. Auditory tracking NMSE was found to vary both as a function of auditory tracking input bandwidth and as a function of the input bandwidth of the visual tracking task performed concurrently. No other significant effect was observed. If we examine Figure 6.8 carefully, we note that the increase in auditory tracking NMSE that follows the visual tracking input bandwidth variable is regular and monotonic for the .49 and 1.84 rad/sec signals; but, for the .86 rad/sec signal bandwidth which the Ss had previously worked with in Experiment 2, we again observe a reduction in the magnitude of visual tracking task interference. This time, the effect becomes ever-more obvious. A small dip when visual homogeneous .86 rad/sec inputs were tracked is also evident in Figure 6.7. The .86 rad/sec practice effect reappears in Figure 6.9 and again in Figure 6.10, but is not evident in Figures 6.11 and 6.12. Thus, if such an effect can be considered a genuine carry-over effect of the type so stressed by Poulton (1974) indicating poor experimental design, it reflects a reduction in tracking NMSE attributable to a reduction in tracking remnant only. If the subject felt more confident tracking the .86 rad/sec homogeneous inputs, this was not indicated by a decrease in τ but by an increase in R_{max}, where, as has been noted before, increases in tracking linearity imply a corresponding decrease in subject output tracking remnant. Overall, however, mean NMSE values were found to increase from .331 for the .49 rad/sec input signal to .461 for the .86 rad/sec input, and to .697 for the 1.84 rad/sec input signal. Indeed, if we now turn to Table 6.18 we note rather large changes in auditory tracking NMSE with visual tracking input bandwidth. The highest value on the table, that of 1.048 for the 1.84 rad/sec homogeneous inputs condition, represents very poor tracking performance indeed; yet that subject's tracking performance on the very same signal was improved drastically when the input signal bandwidth of the visual tracking task was reduced from 1.84 to .49 rad/sec. Auditory mean tracking NMSE was again found to increase with auditory input signal bandwidth, but only the contrasts between the 1.84 rad/sec signal and the .49 and .86 rad/sec signals were significant ($p<.001$).

Tracking linearity R_{max} Measure

Visual Tracking

Average tracking linearity R_{max} values, computed over trial replications, for each visual tracking input signal bandwidth and for each subject individually, were submitted to a two-way analysis of variance comprising the visual tracking input bandwidth variable and the auditory signal bandwidth variable. Mean R_{max} values averaged over trials and subjects are presented in Figure 6.9. Individual subject data are presented in Table 6.20. A summary ANOVA table is presented in Table 6.21.

Visual tracking linearity was found to decrease significantly with corresponding increases in visual tracking input bandwidth. The drop in tracking linearity extended from .980 for the .49 rad/sec input to .977 for the .86 rad/sec input and to .966 for the 1.84 rad/sec input. Visual tracking linearity R_{max} was also found to decrease with the auditory tracking signal bandwidth, but the effect failed marginally to reach significance. There was, nevertheless, a very strong hint that overall visual tracking linearity reduced with increasing auditory forcing function signal bandwidth, as is evident from perusal of Figure 6.9.

Auditory Tracking

Mean auditory tracking R_{max} values averaged over trials and subjects, for each auditory tracking input signal bandwidth and for each subject, were submitted to a two-way analysis of variance comprising the within-subject factors of auditory

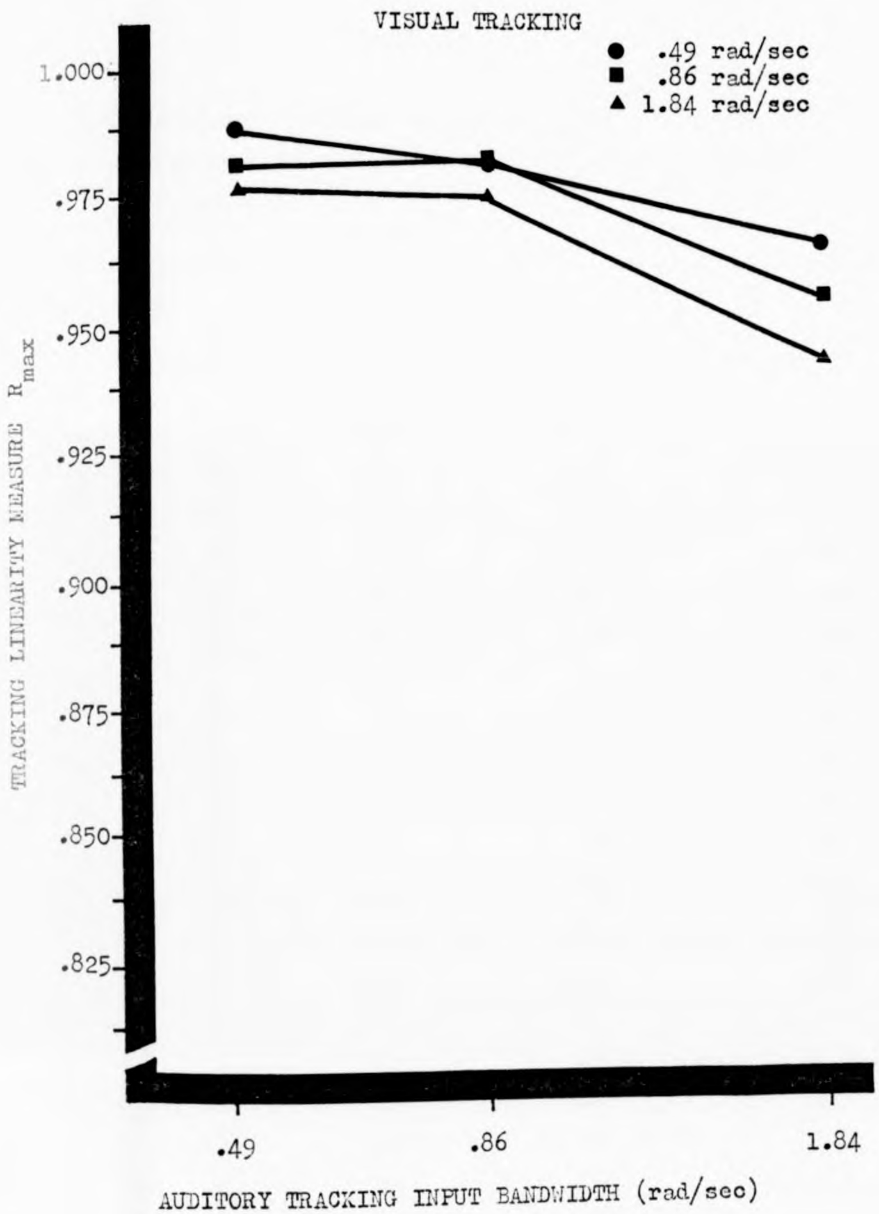

Fig.6.9.-Visual tracking linearity measure R_{max} as a function of input bandwidth in auditory tracking loop. First order control dynamics in both loops.

TABLE 6.20

Average visual tracking linearity, R_{max}, as a function of input bandwidth in both control loops. First order control dynamics. Experiment 3.

VISUAL INPUT (rad/sec)	S	AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1	.985	.994	.973
	2	.990	.992	.984
	3	.979	.954	.968
	4	.987	.980	.931
	5	.992	.989	.984
	6	.994	.991	.968
	$\bar{X}=$	.988	.983	.968
.86	1	.988	.986	.988
	2	.989	.983	.973
	3	.958	.977	.924
	4	.989	.982	.929
	5	.981	.986	.985
	6	.989	.991	.981
	$\bar{X}=$	.982	.984	.963
1.84	1	.985	.984	.979
	2	.981	.967	.972
	3	.952	.962	.912
	4	.988	.988	.863
	5	.980	.982	.975
	6	.979	.972	.974
	$\bar{X}=$	.978	.976	.946

Average of 6 trials per cell.

TABLE 6.21

Summary ANOVA table of average tracking linearity, R_{max}, measure in Experiment 3. First order control dynamics, visual tracking conditions.

Source	DF	SS	MS	F	PROB
Subjects	5	0.008			
Bandwidth {V}	2	0.002	0.001	11.7949	0.0025
EW1B	10	0.001	0.000		
Bandwidth {A}	2	0.006	0.003	3.8040	0.0584
EW2B	10	0.008	0.001		
{V x A}	4	0.000	0.000	0.6129	0.6607
EW12B	20	0.004	0.000		
W	48	0.021			
SQ/N=	51.2538	N= 54	SST=	0.0295	

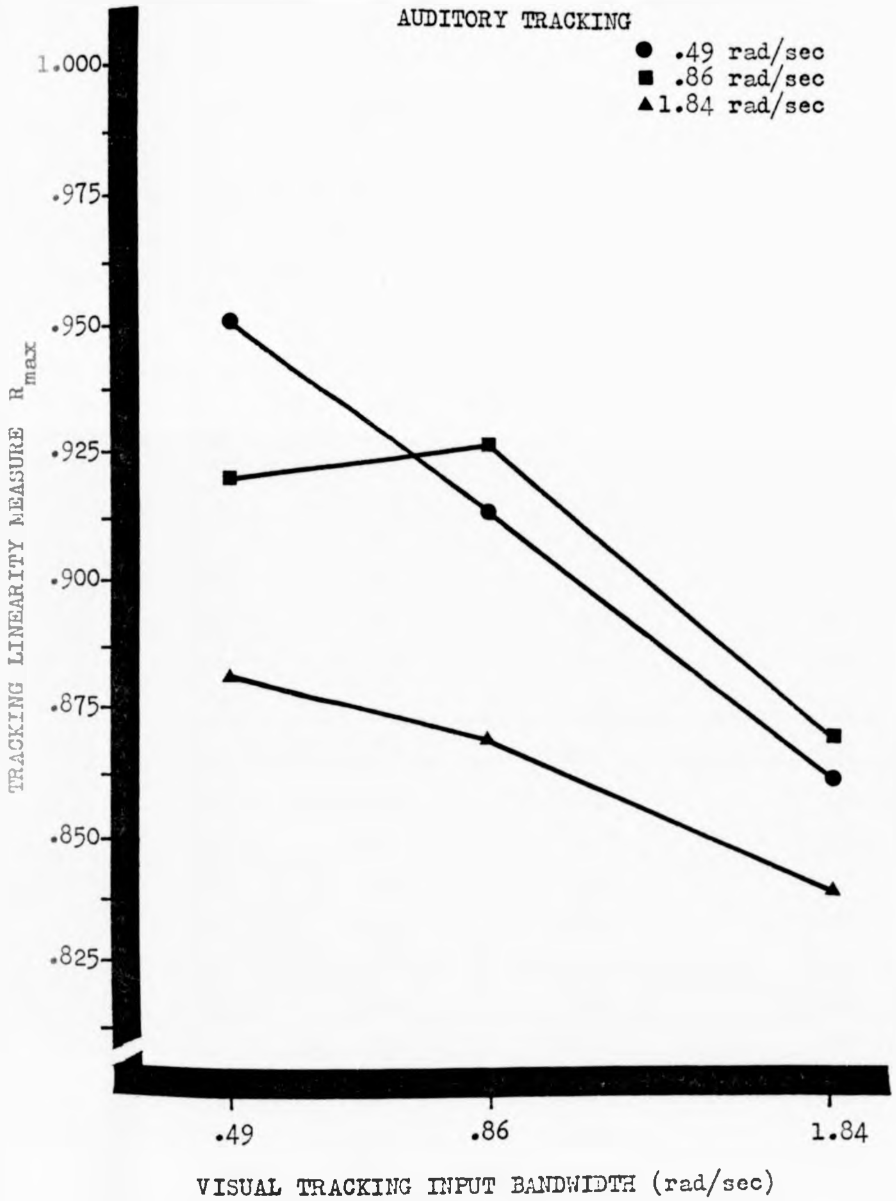

Fig. 6.10.-Auditory tracking linearity measure R_{max} as a function of input bandwidth in visual tracking loop.First order control dynamics in in each loop.

TABLE 6.22

Average auditory tracking linearity, R_{max}, as a function of input bandwidth in both control loops.
First order control dynamics. Experiment 3.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	.961	.942	.913
	2	.919	.892	.826
	3	.959	.885	.916
	4	.943	.882	.847
	5	.957	.952	.928
	6	.967	.930	.735
	$\bar{X}$=	.951	.914	.861
.86	1	.973	.917	.924
	2	.866	.908	.877
	3	.902	.951	.853
	4	.915	.897	.877
	5	.935	.937	.812
	6	.926	.944	.871
	$\bar{X}$=	.920	.926	.869
1.84	1	.923	.920	.839
	2	.834	.894	.844
	3	.859	.878	.854
	4	.859	.858	.813
	5	.891	.867	.875
	6	.922	.789	.819
	$\bar{X}$=	.881	.868	.841

Average of 6 trials per cell.

TABLE 6.23

Summary ANOVA table of average auditory tracking linearity, R_{max}, measures in Experiment 3. First order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	0.018			
Bandwidth {A}	2	0.023	0.011	15.4987	0.0010
EW1B	10	0.007	0.001		
Bandwidth {V}	2	0.036	0.018	14.9267	0.0011
EW2B	10	0.012	0.001		
{A x V}	4	0.006	0.001	0.9054	0.5190
EW12B	20	0.031	0.002		
W	48	0.115			
TSQ/N=	42.9819	N= 54		SST=	0.1325

input bandwidth and visual input bandwidth variable. Mean R_{max} values averaged over subjects are plotted for each auditory tracking input signal bandwidth separately as a function of visual input bandwidth in Figure 6.10. Individual subject data is shown in Table 6.22. A summary ANOVA table is given in Table 6.23.

Auditory tracking linearity was found to decrease significantly with auditory input bandwidth from .909 to .905 to .863 as the auditory forcing function signal bandwidth was increased from .49 to .86 and to 1.84 rad/sec. Only the contrasts between the 1.84 rad/sec signal and each of the other two signals was significant. The only anomaly in the curves in Figure 6.10 is once more that of marked increase in tracking linearity associated with the .86 rad/sec signal. The effect of changing the visual input bandwidth on auditory tracking linearity was relatively more marked in the auditory tracking condition than the converse, but nevertheless the same pattern of results emerges. The accuracy with which the subjects can track a given random signal depends both on its bandwidth (or on the attentional capacity demands set by the task) and on the attentional capacity demands set by another continuous tracking task performed concurrently with it.

Average Response Delay τ Measure

Visual Tracking

Average response delay τ measures averaged over trial replications and subjects, for each visual input signal bandwidth considered, are plotted as a function of corresponding auditory tracking input bandwidth in Figure 6.11. Individual subject data are presented in Table 6.24. These values were then submitted to a two-way analysis of variance comprising the repeated measures factor visual input bandwidth and the auditory input bandwidth factor (representing selective manipulation of the auditory tracking task input bandwidth). A summary ANOVA table is presented in Table 6.25.

Average visual tracking response delay was significantly reduced by some 50 msec when the tracking input bandwidth was increased from .49 rad/sec to .86 rad/sec and to 1.84 rad/sec. Average visual tracking response delay, however, was not found to vary significantly with contingent changes in auditory input bandwidth.

Auditory Tracking

Average response delay τ values were computed for each subject individually, over trial replications, for each

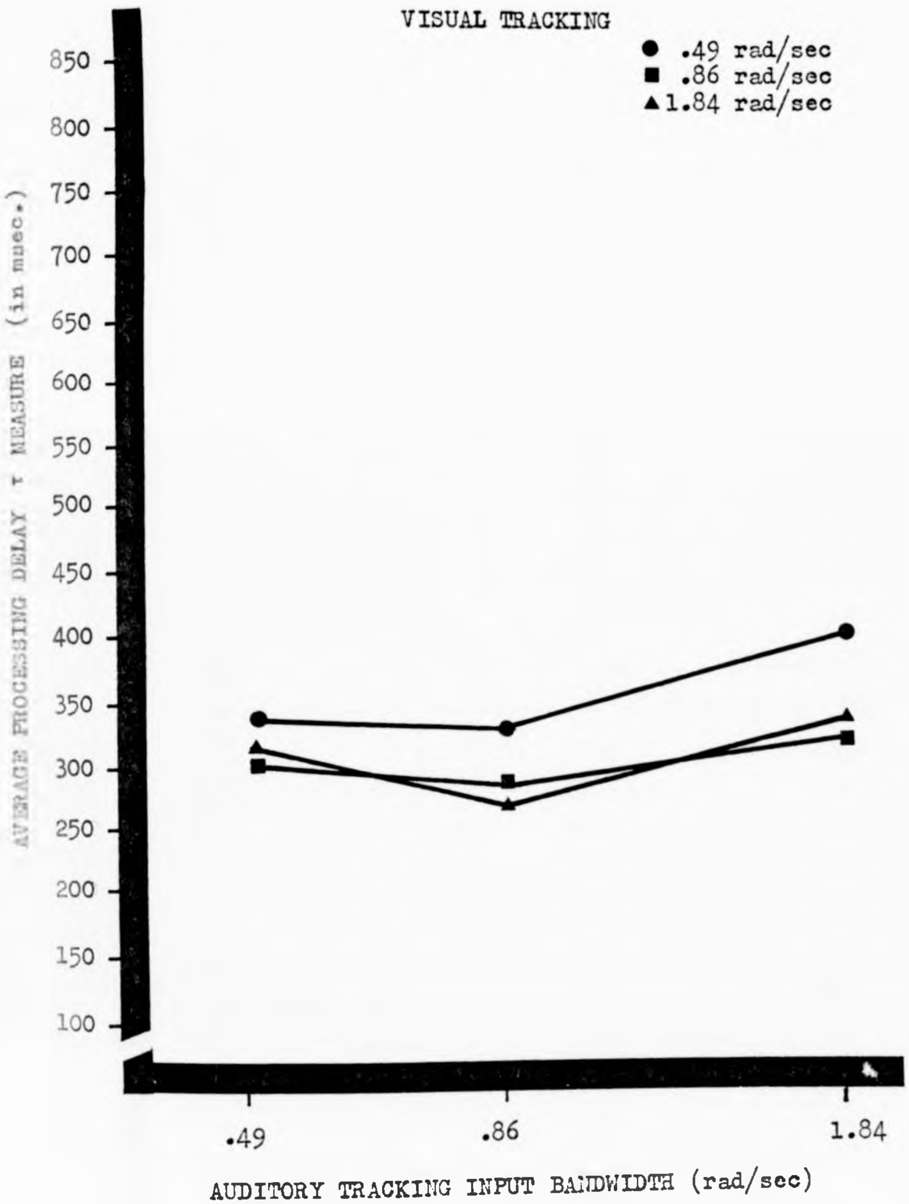

Fig. 6.11.-Average processing delay τ measure as a function of input bandwidth in auditory tracking loop. First order control dynamics in both loops.

TABLE 6.24

Average visual tracking response delay, τ (in msec), as a function of input bandwidth in both control loops. First order control dynamics. Experiment 3.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	300	250	350
	2	300	250	275
	3	525	500	625
	4	275	350	400
	5	275	250	350
	6	350	400	425
	$\bar{X}$=	338	333	404
.86	1	200	250	200
	2	350	275	250
	3	350	325	600
	4	200	350	300
	5	375	250	300
	6	325	275	300
	$\bar{X}$=	300	288	325
1.84	1	200	175	250
	2	300	325	300
	3	500	400	450
	4	250	200	425
	5	300	250	300
	6	350	300	300
	$\bar{X}$=	317	275	338

Average of 6 trials per cell.

TABLE 6.25

Summary ANOVA table of average visual tracking response delay, τ, measures in Experiment 3. First order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	287870.500			
Bandwidth {V}	2	31967.500	15983.750	4.9007	0.0326
EW1B	10	32615.500	3261.550		
Bandwidth {A}	2	30162.000	15081.000	3.2141	0.0827
EW2B	10	46921.000	4692.100		
{V x A}	4	5324.000	1331.000	0.4253	0.7903
EW12B	20	62593.000	3129.650		
W	48	209583.000			

TSQ/N= 5671296.50000 N= 54 SST= 497453.5000

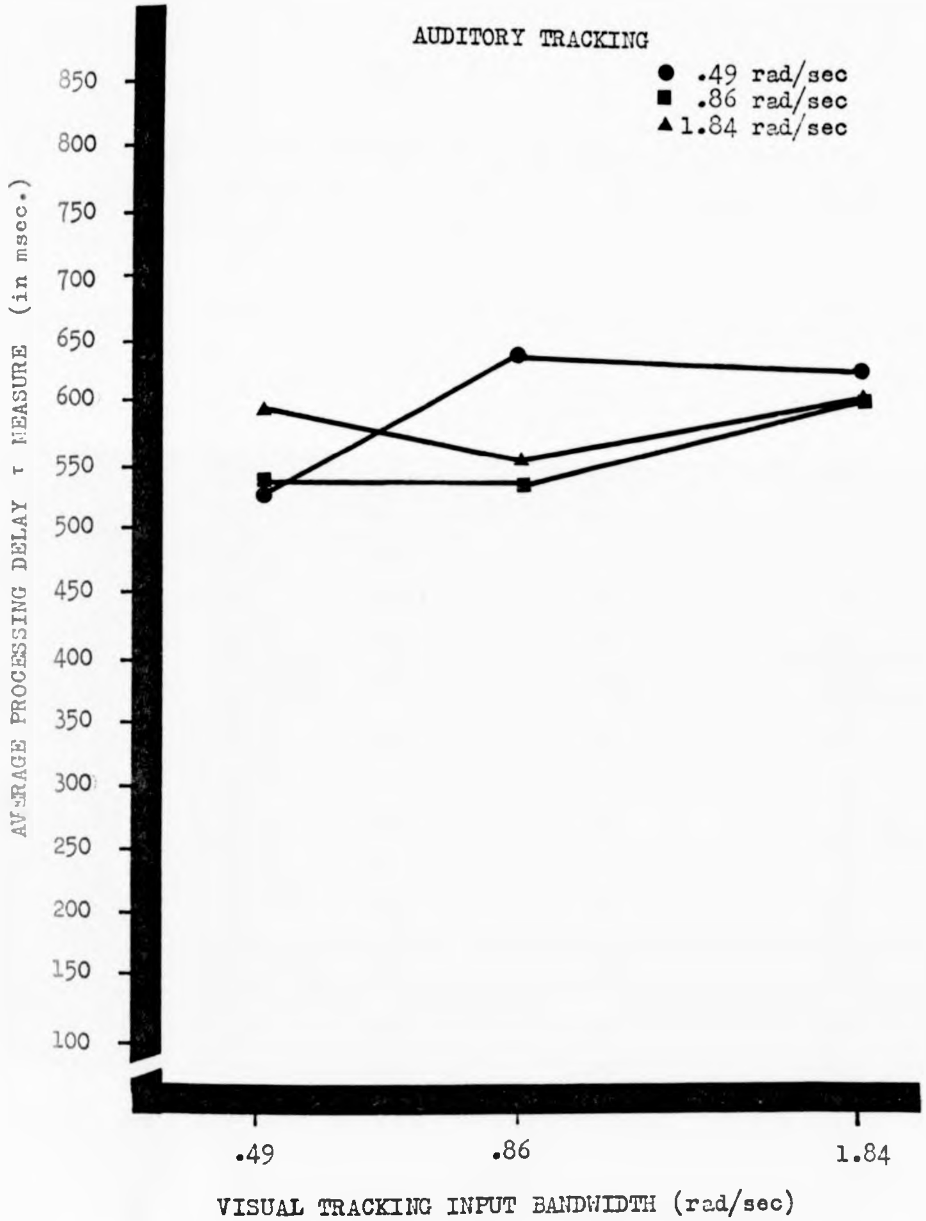

Fig. 6.12.-Average processing delay τ measure as a function of input bandwidth in visual tracking loop. First order control dynamics in each loop.

TABLE 6.26

Average auditory tracking response delay, τ (in msec), as a function of input bandwidth in both control loops. First order control dynamics. Experiment 3.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	500	575	450
	2	650	700	725
	3	675	775	575
	4	425	700	750
	5	525	550	625
	6	350	525	625
	$\bar{X}$=	529	638	625
.86	1	450	350	450
	2	700	750	700
	3	550	550	750
	4	400	575	450
	5	600	550	700
	6	525	450	600
	$\bar{X}$=	538	538	608
1.84	1	500	450	550
	2	600	650	700
	3	775	650	600
	4	475	450	650
	5	700	575	675
	6	525	550	450
	$\bar{X}$=	596	554	604

erage of 6 trials per cell.

TABLE 6.27

Summary ANOVA table of average auditory tracking response delay, τ, measures in Experiment 3. First order control dynamics.

Source	DF	SS	MS	F	PROB
Subjects	5	312976.000			
Bandwidth {A}	2	12106.000	6053.000	0.8368	0.5358
EW1B	10	72336.000	7233.600		
Bandwidth {V}	2	31204.000	15602.000	2.9771	0.0957
EW2B	10	52406.000	5240.600		
{A x V}	4	39630.000	9907.500	1.4897	0.2423
EW12B	20	133012.000	6650.600		
W	48	340694.000			

[illegible]Q/N= 18229456.0000 N= 54 SST= 653670.0000 input signal bandwidth examined. These values were then submitted as for visual tracking data to a two-way analysis of variance with repeated measures on both factors. Mean response delay data averaged over subjects is presented in Figure 6.12. Individual subject data are presented in Table 6.26. None of the effects investigated was statistically significant, although there was nevertheless a hint of an increase in auditory tracking τ as the visual forcing function bandwidth was raised from .86 to 1.84 rad/sec. A comparable, but also small, increase in visual tracking τ is also discernible in Figure 6.12. Given the low forcing function bandwidths involved, it would not be entirely justified to dismiss the result of such an effect altogether; rather, it would be of future interest to investigate the functional relationships between τ and R_{max} in homogeneous input conditions such as the ones examined in this experiment. We note, however, that in Figure 6. visual tracking τ measures, if anything, decreased with auditory input bandwidth.

Correlation between the Absolute Tracking Error Signals

The average correlation coefficient between the absolute tracking error signals $e_v(t)$ and $e_a(t)$ for each subject in the homogeneous and heterogeneous input conditions appears in Table 6.29. We note very few values exceed the $\pm$.087 range

TABLE 6.28

Average correlation values, r, between the absolute tracking error signals in the homogeneous and heterogeneous inputs conditions in Experiment 3. First order control dynamics.

VISUAL INPUT (rad/sec)	S	AUDITORY INPUT (rad/sec) .49	.86	1.84
.49	1	-.05	.053	.070
	2	.055	.029	-.068
	3	-.175	.203	.055
	4	-.016	.090	.046
	5	.119	.128	.074
	6	.039	-.006	-.015
	$\bar{X}$=	-.005 (.10)	.083 (.08)	.027 (.06)
.86	1	.099	.131	.079
	2	.057	.096	-.027
	3	.196	-.164	.032
	4	.173	.116	.126
	5	.088	.029	.177
	6	.019	-.022	.094
	$\bar{X}$=	.105 (.07)	.031 (111)	.080 (.07)
1.84	1	.007	-.048	.123
	2	-.087	-.002	.060
	3	-.050	.074	.059
	4	.050	-.055	.233
	5	-.053	-.038	.022
	6	.021	.036	-.034
	$\bar{X}$=	-.019 (.05)	-.006 (.05)	.077 (.09)

Average of 6 trials in each cell. Values within parentheses represent standard deviation.

which would qualify a significant ($p<.05$) correlation between the signals. The majority of these values could be attributable to subjects 3 and 4. Nevertheless, these values are not large and not consistent in sign either between or within subjects or conditions. The only overall significant correlation value observed in the table occurred when the forcing functions were heterogeneous, with a .86 rad/sec visual input and a .49 rad/sec auditory input presented simultaneously. This result may well be unreplicable but suggests that for this condition at least the absolute visual and auditory tracking error signals were somewhat more similar to each other than in other conditions. There is, however, no evidence of serial tracking error reducing activity associated with either heterogeneous or homogeneous increases in system input bandwidth.

Correlation between the Subject's Control Command Signals $c_v(t)$ and $c_a(t)$

Van Lunteren's (1977) observation of linear response crosscoupling in multiple single-loop control of a first order visual compensatory tracking system was not confirmed. The correlation coefficient relating the $c_v(t)$ and $c_a(t)$ signals showed no evidence of a symmetrical component in subjects' tracking responses: that is, there was no evidence of a tendency for the subject to respond in mirror-image fashion when tracking the visual and auditory input signals simultaneously with zero order controls.

It should be noted, however, that Van Lunteren observed linear crosscoupling signal power between the loops using frequency domain analysis. Linear relationships established in the frequency domain may not be sensitive to signal differences in phase between the signals. Thus, if we simply correlate the signals, the correlation coefficient may introduce bias against such an effect. In this part of the experiment the possibility that subjects' tracking responses do tend to be emitted in mirror-image fashion when controlling a multiple single-loop system, but only more or less sequentially, was tested. This possibility was tested by examining the cross-correlation function and noting the peak value and time of occurrence. If the subject's controlling responses are so co-ordinated, it may, therefore, be possible to ascertain to what extent.

The average crosscorrelation function peak values nd the average time of its occurrence along the function, for ch subject, in each condition, appear in Table 6.28. Two clear sults emerge. Firstly, there is a considerable number of negative rrelation coefficients present. Secondly, the relative differ-ce in lag between the signals was found to increase with forcing nction input bandwidth. We note that a significant ($r > \pm .087$)

TABLE 6.29

Average crosscorrelation peak values between the operator's control command movement signals $c_v(t)$ and $c_a(t)$ with homogeneous and heterogeneous inputs. First order control dynamics. Experiment 3.

AUDITORY INPUT (rad/sec)	S	VISUAL INPUT (rad/sec) .49	.86	1.84
.49	1	.166	-.050	-.045
	2	.053	.057	.027
	3	-.063	-.115	.088
	4	-.026	-.144	-.187
	5	-.282	-.046	.210
	6	.234	.019	-.089
	$\bar{X}$=	.039 (40)	-.047 (442)	.001 (292)
.86	1	.042	-.276	-.147
	2	-.015	-.196	-.108
	3	-.199	-.303	-.175
	4	.009	-.311	-.160
	5	-.026	-.129	-.129
	6	.043	.069	-.190
	$\bar{X}$=	-.024 (17)	-.191 (75)	-.152 (246)
1.84	1	-.005	-.252	-.318
	2	.125	-.175	.033
	3	-.063	-.364	.153
	4	-.045	-.313	-.110
	5	.207	-.278	.023
	6	.150	-.139	.219
	$\bar{X}$=	-.008 (0)	-.254 (359)	.000 (334)

Average of 6 trials in each cell. Values in brackets represent average response time difference τ $c_v(t)c_a(t)$ (in msec) between the operator response signals.

correlation coefficient can be taken as evidence in support of the notion that subjects' responses tend to mirror each other when tracking two single loops, but not quite symmetrically, since the relative difference in phase between the signals was some 359 msec. These data, however, do not generalize to all subjects in all conditions, making it impossible to claim that there is always crosscoupling between the loops.

It cannot be denied that in some instances there was some crosscoupling between the loops, but it is questionable whether this crosscoupling was responsible for the orderly interference time-sharing effects noted between the tasks: even the issue of whether this crosscoupling term originates from equalizing characteristics established when subjects track heterogeneous input signal bandwidths cannot be reliably answered, because it was present in both the .86 rad/sec homogeneous condition as well as the .86 rad/sec visual and 1.84 rad/sec auditory, and 1.84 rad/sec visual and .86 rad/sec auditory heterogeneous input conditions.

DISCUSSION

The results of this experiment, both for zero and for first order control dynamics, are decidedly in favor of the undifferentiated capacity hypothesis. Tracking NMSE associated with the performance of either of two visual and auditory tracking tasks performed concurrently was found to depend on the input bandwidth of the other. Such interdependence between the tasks, even for forcing function bandwidths as low as the ones used in this experiment, is evidence against the notion that attentional resources are allocated in fixed amounts to meet the information processing demands of each task. It is unlikely, moreover, that the observed multitask interference effects observed were due to the fact that the attentional demands placed by the tasks exceeded the total available capacity. The possibility that response interference was a major contributor to the effects is greatly weakened by the observation that in Experiment 1, where homogeneous input bandwidth conditions were used throughout, the tracking/copying, dual-task, time-shared tracking conditions, did not lead to reductions of performance nearly as great as those observed in simultaneous bimodal tracking conditions. There were hints of linear crosscoupling between the loops, however, but such crosscoupling was found in the homogeneous bandwidth conditions (see Van Lunteren's (1977) study) as well as being observed in the heterogeneous bandwidth conditions. In addition, the crosscoupling effects noted were not distributed between subjects or conditions as evenly as were the experimental main effects. Crosscoupling between the loops, therefore, does not appear to be a likely candidate to account for the observed effects. If the effects observed reflect the dynamics of man's attentional process, an undifferentiated capacity hypothesis, on the other hand, would fit squarely with these results. If tracking NMSE associated with the performance of a given task was found to vary with the informational content of another task performed concurrently, this effect was attributable to contingent variation in tracking linearity but not to average response delay.

Response variability effects are consistent with the notion that the noise injection, or remnant portion, of the operator's response was a major contributor to increases in NMSE. This result is in turn consistent with both the undifferentiated capacity hypothesis and the related multiple channel model of task interference proposed and developed by Levison (1969) and his colleagues at Bolt, Beranek and Newman, which has been described earlier. Since one effect of divided attention is to induce variation in the signal-to-noise ratio along the various information processing channels, a noise-induced effect in tracking the heterogeneous input conditions may well underlie the effect. Levison, Elkind and Ward (1971) suggested, quite emphatically, that noise injection, and not processing delay or other factors, accounts for multitask interference. This is perhaps a strong position to take a likely candidate to account for the observed effects. If the effects observed reflect the dynamics of man's attentional process, an undifferentiated capacity hypothesis, on the other hand, would fit squarely with these results. If tracking NMSE associated with the performance of a given task was found to vary with the informational content of another task performed concurrently, this effect was attributable to contingent variation in tracking linearity but not to average response delay.

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It should be noted, moreover, that these effects were obtained even when the forcing function input signal bandwidths considered were very low. Whether more decidedly concave upward nonlinearities in τ would have been observed had higher input bandwidths been chosen is of interest. However, if we consider the values observed in the auditory tracking tasks we note that these values are considerably greater than those observed when tracking was visual. The auditory tracking task was always deemed the more difficult of the two, yet no obvious consistent nonlinearities in auditory tracking are evident. In any event, it would appear that the contribution to NMSE by decreasing R_{max} was considerably greater than that attributable directly to increased τ. This effect may have important implications when viewed in the general context of an interplay between R_{max} and τ in producing time-shared tracking decrements in performance.

Neither homogeneity nor heterogeneity in bandwidth seems to give rise to the negative correlation between the absolute tracking error signals predicted by single-task, serial model: rather, it would appear once again that the effect of increasing the bandwidth both within and between the tracking loops would have little effect on subjects' error-reducing behavior. Overall, the magnitude of tracking error in one loop was not dictated directly by the magnitude of error in the other loop. Hence, it would appear that the subjects were indeed tracking the signals as distinct input sources.

In the present study one of two concurrent tasks is held constant while aspects of the other are manipulated. The power of the technique is shown when we consider some interesting suggestions for further research. It would be of interest, for example, to ascertain whether task performance difficulty, which may relate directly to mental effort, or workload, is a continuous additive process. Consider a situation in which the input signal bandwidths considered are heterogeneously and homogeneously presented, as was the case in this experiment. Consider, further, that we had employed signal bandwidths of .57, .86 and 1.14 rad/sec instead of the .49, .86 and 1.84 rad/sec logarithmically-spaced signals used here. We would replicate the experiment but this time we would be able to determine whether tracking two .86 rad/sec signals simultaneously - which, in combination, would demand a given (finite) amount of attentional resources - is equivalent to tracking heterogeneous input signals of .57 and 1.14 rad/sec simultaneously. If it is, then it could be argued that if X amount of attentional resources is allocated to the processing of the .57 rad/sec signal, and Y resources to processing the 1.14 rad/sec signal, and this allocation policy produces heterogeneous tracking performance which is not different from that when homogeneous .86 rad/sec input signals are tracked, then the attentional resources allocated to the 1.14 rad/sec signal Y could be considered equal to twice those allocated to .57 rad/sec signal. If, on the other hand, tracking performance of homogeneous .86 rad/sec signals differs radically from the .57 and 1.14 rad/sec heterogeneous input signal tracking condition, then such a linear algebra of attentional resources would be impossible. Unfortunately, we cannot tell much from the NMSE tables in this experiment about the truth or falsity of this, but only note the consistent difference in tracking performance between visual and auditory tracking. The visual .49 and auditory 1.84 rad/sec heterogeneous input tracking NMSE values often differed from those obtained when the auditory .49 and 1.84 rad/sec heterogeneous input conditions were performed.

CHAPTER 7.

7.1. - Experiment 4: Homogeneous Inputs, Homogeneous and Heterogeneous Controlled Element Dynamics.

Conceptually, the research strategy used in the experiment was essentially that used in Experiment 3. In a variant of the time-sharing paradigm, subjects' performance of a continuous compensatory tracking task was examined as the controlled element dynamics of another continuous compensatory task performed conceurrently were selectively varied. Subjects were required to control both with homogeneous and heteregeneous controlled element dynamics. The control dynamics investigated were proportional, rate and acceleration, in every possible combination between the visual and auditory control loops. Because Experiment 2 had revealed that subjects could not track sufficiently well the auditory input with acceleration controls, the acceleration control dynamics in the auditory tracking conditions were not implemented.

METHOD

Subjects:

The same six subjects who took part in Experiment 3 returned to take part in this experiment. The experiment was run approximately four weeks after completion of Experiment 3. As

In the other experiments, subjects were recruited and paid £0.60/hr. The subjects were again told that the subject with the lowest tracking NMSE would receive a £2.00 bonus at the end of the experiment.

Apparatus and Materials:

The same apparatus used in Experiment 3 was used, the only exception being that of appropriate alterations in the analog computer program carried out in order to provide the various control dynamics in each tracking loop. The .49 rad/sec forcing function used in Experiment 2 were also used in this experiment. The amplitude of each of the component sinusoids in the shelf was 1/10th that of of the sinusoidal components in the main part of the signal. The signals were normalized to a 4.81 cm RMS deflection on the screen, as in the previous experiments.

Procedure

Subjects returned to take part in five 1 hour daily sessions. The first two sessions were allocated to practice, and the last three sessions were experimental sessions. Subjects were introduced to the various control dynamics and were given an average of six practice trials in each condition on each day. Each trial lasted 71.2 seconds. Tracking data was collected during a 1.2 sec interval commencing 20 secs after the beginning of the trial. The visual and auditory forcing functions $i_v(t)$ and $i_a(t)$, the subject's control command signals $c_v(t)$ and $c_a(t)$, and the system output signals $m_v(t)$ and $m_a(t)$, were sampled on-line at the rate of 10 samples/sec. These data were then stored on magnetic tape for subsequent off-line analyses.

After the two practice sessions the subjects returned on three consecutive days to take part in the other three experimental sessions. Subjects took part in two different tracking conditions on each day. The presentation of conditions was counterbalanced between subjects on each day. In order to eliminate carry over effects, the order of control was raised progressively over the three day period. The various condition presentation orders for each subject, over the three sessions, is given in Table 7.1.

During each experimental session, subjects performed a number of practice trials until performance became stable. Six experimental trials were then administered, giving a total of approximately twelve trials in each tracking condition. Between tracking conditions, the subjects were given approximately five to ten minutes rest. During this interval, E made appropriate changes in the analog computer program, and checked the calibration of the various analog computer elements.

TABLE 7.1

Condition presentation order in Experiment 4.

S	CONDITION Day 1		Day 2		Day 3	
1	(0,1)	(0,0)	(1,1)	(1,0)	(2,1)	(2,0)
2	(0,0)	(0,1)	(1,0)	(1,1)	(2,0)	(2,1)
3	(0,1)	(0,0)	(1,1)	(1,0)	(2,1)	(2,0)
4	(0,0)	(0,1)	(1,0)	(1,1)	(2,0)	(2,1)
5	(0,1)	(0,0)	(1,1)	(1,0)	(2,1)	(2,0)
6	(0,0)	(0,1)	(1,0)	(1,1)	(2,0)	(2,1)

Note: Zero,first, and second order control are represented in the table by the numbers 0,1, and 2. The first element of each pair in brackets represents the order of control dynamics in the visual tracking loop. The second element represents the controlled element dynamics in the auditory tracking loop. The cell (2,1), therefore, represents visual tracking with acceleration control dynamics, and concurrent auditory tracking with rate control dynamics.

RESULTS

Analysis of Tracking NMSE Measures.

Visual Tracking

Average NMSE values, computed over trials, for each subject, in each homogeneous and heterogeneous control dynamics condition are presented in Table 7.2. These values were then submitted to a two-way analysis of variance with repeated measures on both factors. One of these factors related specifically to the visual tracking task order of control manipulation. The other factor related average visual tracking NMSE to the order of control dynamics used in performing the auditory tracking task. A summary ANOVA table appears in Table 7.3. Average visual tracking NMSE values, computed over trials and subjects are plotted for each order of control as a function of auditory tracking control dynamics in Figure 7.1.

Examination of Table 7.3 reveals that only the visual tracking order of control manipulation yielded consistent and statistically significant variation in visual tracking NMSE measures. Increasing the order of control from zero, to first, and then to second order, produced corresponding increases in tracking NMSE from .041, to .054, to .442. Visual tracking NMSE, however, was not found to vary significantly with changes in the auditory

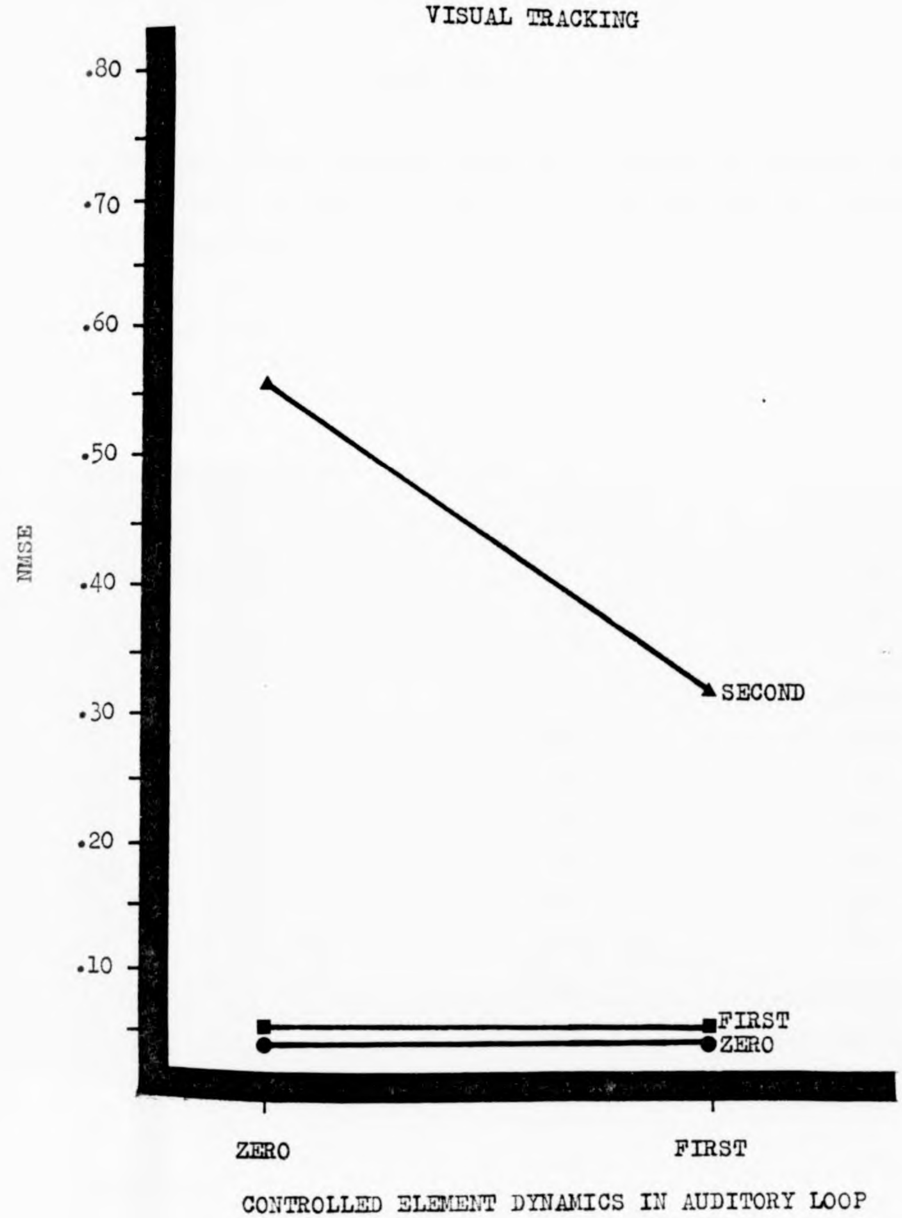

Fig. 7.1.- Visual tracking NMSE as a function of control dynamics in the auditory loop. Homogeneous .49 rad/sec inputs

TABLE 7.2

Average visual tracking, NMSE, as a function of controlled element dynamics in both tracking loops. Homogeneous .49 rad/sec inputs. Experiment 4.

VISUAL TRACKING CONTROL DYNAMICS	S	AUDITORY TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE
PROPORTIONAL	1	.040	.025
	2	.036	.034
	3	.044	.042
	4	.025	.032
	5	.028	.044
	6	.075	.065
		$\bar{X}$= .041	.040
RATE	1	.036	.028
	2	.061	.044
	3	.062	.071
	4	.061	.067
	5	.048	.051
	6	.060	.058
		$\bar{X}$= .054	.053
ACCELERATION	1	.319	.303
	2	.435	.231
	3	1. 80	.573
	4	.313	.217
	5	.308	.251
	6	.493	.377
		$\bar{X}$= .558	.325

Average of 6 trials per cell.

TABLE 7.3

Summary ANOVA table of average visual tracking NMSE measures in Experiment 4.

SOURCE	DF	SS	MS	F	PROB
Subjects	5	0.307			
Control Order {V}	2	1.245	0.622	11.2454	0.0029
EW1B	10	0.553	0.055		
Control Order {A}	1	0.055	0.055	2.9940	0.1426
EW2B	5	0.092	0.018		
{V x A}	2	0.107	0.054	2.8037	0.1069
EW12B	10	0.191	0.019		
W	30	2.244			

ΣSQ/N= 1.1510 N= 36 SST= 2.5513

tracking task control dynamics. If we examine Figure 7.1 we note no change in tracking NMSE when subjects were required to perform visual tracking with zero order control dynamics and auditory tracking with first order controls simultaneously, relative to a homogeneous control dynamics condition where subjects performed visual and auditory tracking with zero order control dynamics in each loop. This relationship is represented by the lowest curve on the graph. Parallel to this curve and above it, we find the curve relating first order visual and zero order auditory tracking condition NMSE to that in first order, homogeneous dynamics, visual and auditory tracking conditions. Average visual tracking NMSE in this latter condition is represented by the rightmost point in the curve. Visual tracking NMSE did not vary significantly when the auditory tracking control dynamics were changed from zero ro first order. It would appear, therefore, that for the very low forcing function input signal bandwidth considered, the heterogeneity in control dynamics between zero and first order control was not a serious impediment to the concurrent performance of the tracking tasks. This was only true, however, for zero and first order control dynamics. As is evident in Figure 7.1, tracking NMSE was highest when visual tracking was performed with second order, and auditory tracking with zero order control dynamics. We note, however, that the curve dips rapidly when the auditory tracking control dynamics are reduced from zero order to first order. Reducing the discrepancy in control dynamics between the loops, therefore, produced a corresponding reduction in visual tracking NMSE ($p<.05$). This result confirms that initially obtained in two-axis visual tracking tasks, by Chernikoff, Duey and Taylor (1960), and Chernikoff and Lemay (1963) showing that the effect also occurs across sensory modalities. As has already been noted, this effect was not found when low orders of control were involved. This result, in turn, suggests that because the forcing function bandwidth was so low the subjects were able to generate the various equalizer characteristics with little, or no, detectable intertask interference when using low orders of control. When second order control dynamics were introduced, however, the heterogeneity between the control dynamics was the crucial determinant of visual tracking NMSE. The possibility of task interference arising from accompanying changes in error signal bandwidth heterogeneity between the tracking loops, is not ruled out.

Auditory Tracking.

Average auditory tracking NMSE values computer over trials, for each subject, in each of the heterogeneous and homogeneous control conditions are presented in Table 7.4. These values were then submitted to a two-way analysis of variance with repeated measures on both factors. One factor related auditory tracking NMSE to order of control dynamics variation, where auditory tracking NMSE was performed with either zero, or first order controls.

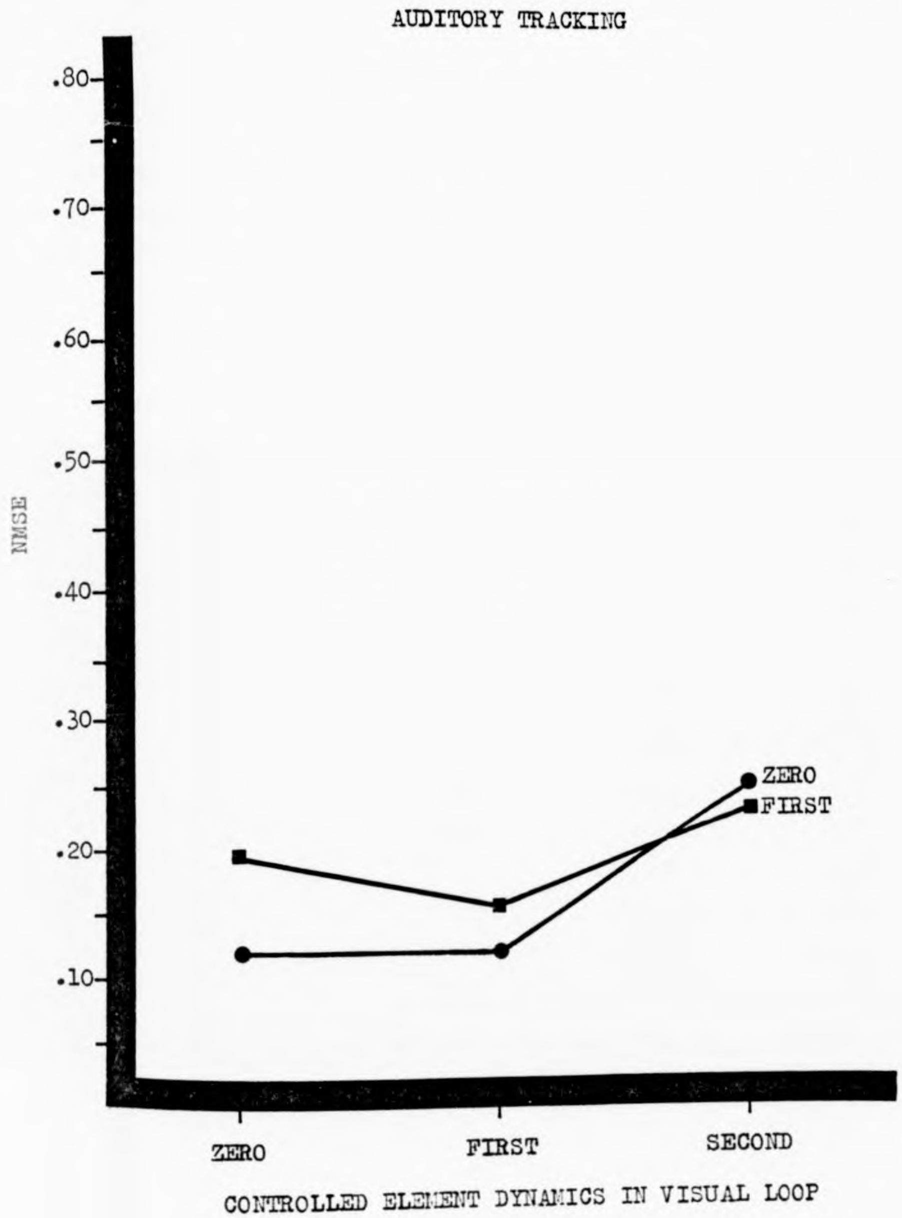

Fig. 7.2.- Auditory tracking NMSE as a function of control dynamics in the visual loop.Homogeneous .49 rad/sec inputs

TABLE 7.4

Average auditory tracking, NMSE, as a function of controlled element dynamics in both tracking loops. Homogeneous .49 rad/sec inputs. Experiment 4.

AUDITORY TRACKING CONTROL DYNAMICS	S	VISUAL TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE	ACCELERATION
PROPORTIONAL	1	.108	.124	.214
	2	.163	.157	.214
	3	.099	.102	.226
	4	.098	.152	.200
	5	.190	.097	.530
	6	.080	.088	.122
		$\bar{X}$= .124	.120	.251
RATE	1	.135	.131	.198
	2	.296	.241	.455
	3	.110	.096	.142
	4	.192	.128	.178
	5	.297	.194	.235
	6	.113	.145	.173
		$\bar{X}$= .191	.157	.230

verage of 6 trials per cell.

TABLE 7.5

Summary ANOVA table of average auditory NMSE measures in Experiment 4.

SOURCE	DF	SS	MS	F	PROB
Subjects	5	0.113			
Control Order {A}	1	0.007	0.007	0.9914	0.6329
EW1B	5	0.034	0.007		
Control Order {V}	2	0.072	0.036	12.4731	0.0020
EW2B	10	0.029	0.003		
{A x V}	2	0.012	0.006	1.0975	0.3722
EW12B	10	0.055	0.005		
W	30	0.208			
TSQ/N=	1.1468	N= 36		SST=	0.3218

the other, related auditory tracking NMSE to changes in order of control in the visual tracking task. A summary ANOVA table appears in Table 7.5. Mean NMSE values, computed over trials and subjects, for the zero and first order control dynamics conditions are plotted as a function of visual tracking order of control in Figure 7.2.

When subjects performed auditory tracking with zero order control dynamics the observed NMSE value was .165, whereas when the order of control was raised to first order, a non significant increase in NMSE to .192 was observed. Overall, auditory tracking NMSE was found to vary significantly when the control dynamics in the visual tracking task were changed from zero to first, or to second order. This main effect was largely attributable to a considerable increase in tracking NMSE which accompanied the changes in visual control dynamics from first to second order ($p<.01$). Raising the visual tracking order of control from zero to first order did not affect auditory tracking NMSE in any obvious way. Exmination of Figure 7.2, reveals once more, that tracking NMSE was highest in the second/zero order heterogeneous control dynamics condition, the uppermost point in the graph. Relative to the zero order homogeneous control dynamics condition, the introduction of second order control dynamics in the visual tracking loop produced a significant ($p<.01$) decrement in auditory tracking performance. When first order control dynamics were introduced in the visual tracking loop, the effect was not statistically significant. In these conditions, where auditory tracking was carried out with first order control dynamics, the first order homogeneous condition yielded the lowest auditory tracking NMSE. The introduction of zero order visual tracking control dynamics produced a non significant relative decrement in auditory tracking performance. When second order controls were introduced in the visual tracking loop, however, decrement in auditory tracking performance was more pronounced. This effect however, was not statistically significant. Examination of individual subject, auditory tracking performance in Table 7.4, shows that most subjects showed the effect. Moreover, the results obtained in the auditory tracking conditions confirm and support the notion that the heterogeneity of control dynamics in multiple single-loop control produces changes in compensatory tracking NMSE which might be thought to arise from central information processing limitations, and which are not attributable to within-modality interference.

Analysis of Tracking Linearity Measure R_{max}.

Visual Tracking

Average visual tracking linearity measure R_{max} values computed over trial replications, for each subject individually, in each homogeneous and heterogeneous control dynamics condition,

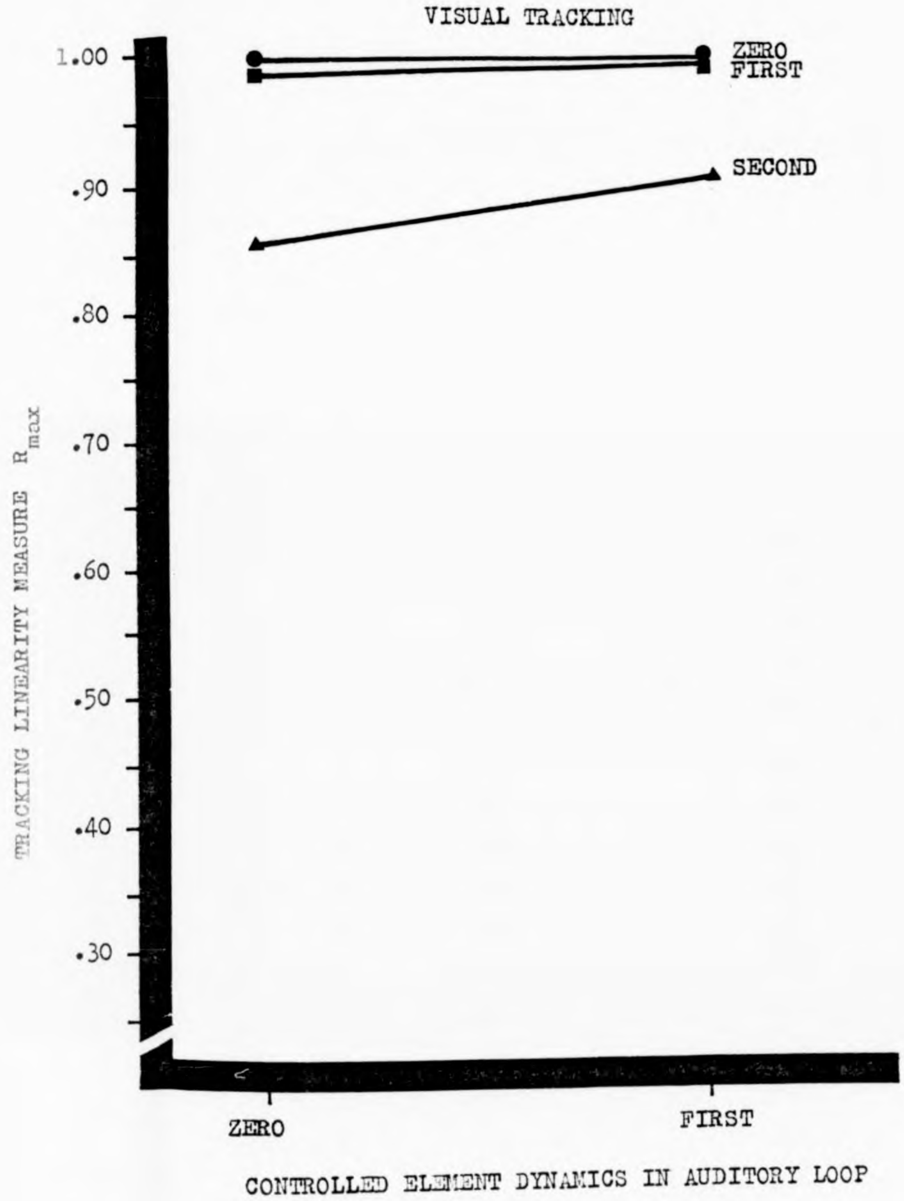

Fig.7.3.- Visual tracking linearity measure R_{max} as a function of control dynamics in the auditory loop. Homogeneous .49 rad/sec inputs

TABLE 7.6

Average visual tracking linearity, R_{max}, as a function of controlled element dynamics in both tracking loops. Homogeneous .49 rad/sec inputs. Experiment 4.

VISUAL TRACKING CONTROL DYNAMICS	S	AUDITORY TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE
PROPORTIONAL	1	.992	.994
	2	.992	.994
	3	.992	.992
	4	.996	.992
	5	.997	.989
	6	.988	.990
		$\bar{X}$= .992	.992
RATE	1	.992	.995
	2	.987	.991
	3	.979	.986
	4	.989	.988
	5	.992	.992
	6	.963	.987
		$\bar{X}$= .984	.990
ACCELERATION	1	.917	.915
	2	.871	.933
	3	.659	.842
	4	.909	.925
	5	.905	.923
	6	.857	.906
		$\bar{X}$= .853	.907

Average of 6 trials per cell.

TABLE 7.7

Summary ANOVA table of average visual tracking linearity, R_{max}, measures in Experiment 4.

SOURCE	DF	SS	MS	F	PROB
Subjects	5	0.016			
Control Order {V}	2	0.096	0.048	17.9371	0.0006
EW1B	10	0.027	0.003		
Control Order {A}	1	0.004	0.004	4.1915	0.0940
EW2B	5	0.004	0.001		
{V x A}	2	0.005	0.003	3.7025	0.0619
EW12B	10	0.007	0.001		
W	30	0.0143			
TSQ/N=	32.7012	N= 36		SST=	0.1591

are presented in Table 7.6. These means were submitted to a two-way analysis of variance comprising two chief factors (1) a visual tracking order of control factor with three levels of corresponding to zero, first, and second order controlled element dynamics, and (2) an auditory tracking order of control factor with two levels, corresponding to zero and first order controlled element dynamics. A summary ANOVA table appears in Table 7.7. These mean averaged over subjects for zero, first, and second order control dynamics, are plotted as a function of order of control dynamics in the auditory tracking loop in Figure 7.3.

Examination of Table 7.6 reveals that when visual tracking was performed with zero order proportional control, R_{max} values were not significantly different in the zero order/first order heterogeneous control dynamics condition from those obtained in the first order homogeneous control dynamics condition. When the control dynamics in the visual tracking loop were first order control, and those in the auditory tracking loop were zero order, a small but not statistically significant decrement in visual tracking linearity was observed relative to the first order homogeneous control dynamics condition. When the subjects performed visual tracking with second order control dynamics, average visual tracking R_{max} measures were lowest. When the auditory tracking control dynamics were zero order, R_{max}

values in this condition were found to increase significantly ($p<.05$) if the control dynamics in the auditory tracking loop were raised to first order. Table 7.7 indicates that average visual tracking linearity measures R_{max} varied significantly as the controlled element dynamics were raised from zero to first and to second order. Visual tracking linearity, however, was not found to vary significantly as a function of the order of control dynamics in the auditory tracking loop. The only significant contrast of interest was that relating second order control visual tracking R_{max}, when the auditory tracking controlled element dynamics were raised from zero order to first order ($p<.05$). Hence, it would appear that tracking linearity is a major factor in determining the magnitude of tracking NMSE as the degree of heterogenity in control dynamics between the loops is varied. This, in turn, implies that one effect on visual tracking performance of increasing the order of control dynamics in the auditory tracking loop, was to increase the average amplitude of visual tracking remnant. Thus, as the information processing demands associated with the performance of the auditory tracking task were increased the amount of information processing associated with the performance of the visual tracking task was correspondingly reduced.

Auditory Tracking

Mean auditory tracking linearity estimate R_{max} values, computed over trial replications, for each subject, in the

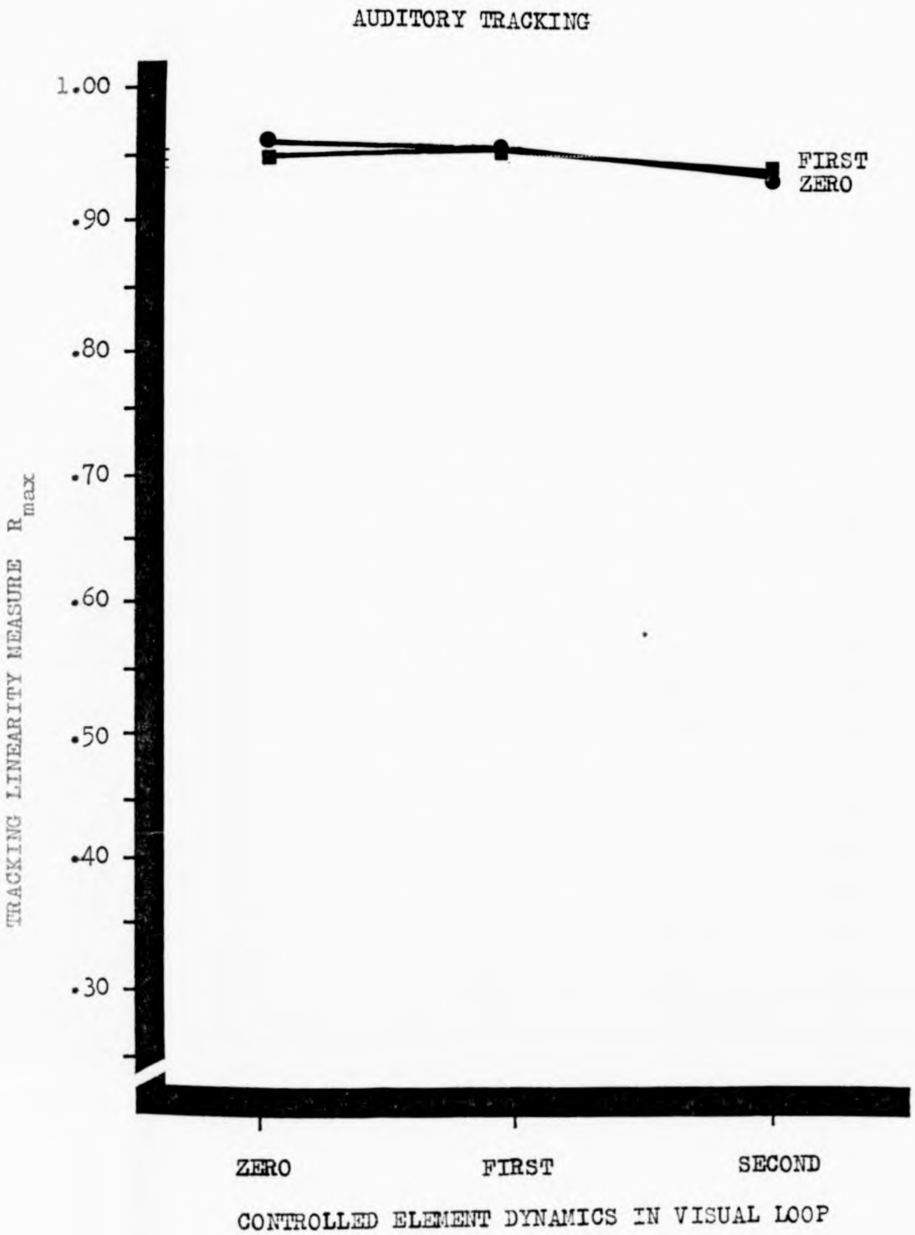

Fig.7.4.- Auditory tracking linearity measure R_{max} as a function of control dynamics in the visual loop. Homogeneous .49 rad/sec inputs.

TABLE 7.8

Average auditory tracking linearity, R_{max}, as a function of controlled element dynamics in both tracking loops. Homogeneous .49 rad/sec inputs. Experiment 4.

AUDITORY TRACKING CONTROL DYNAMICS	S	VISUAL TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE	ACCELERATION
	1	.964	.945	.927
	2	.957	.953	.954
	3	.979	.972	.946
PROPORTIONAL	4	.966	.935	.916
	5	.916	.966	.925
	6	.975	.966	.962
	$\bar{X}$=	.960	.956	.938
	1	.966	.958	.937
	2	.904	.942	.887
RATE	3	.974	.961	.973
	4	.935	.964	.955
	5	.937	.942	.939
	6	.963	.961	.953
	$\bar{X}$=	.947	.955	.941

verage of 6 trials per cell.

TABLE 7.9

Summary ANOVA table of average auditory tracking linearity, R_{max}, measures, in Experiment 4.

SOURCE	DF	SS	MS	F	PROB
Subjects	5	0.006			
Control Order {A}	1	0.000	0.000	0.2324	0.6517
EW1B	5	0.003	0.001		
Control Order {V}	2	0.002	0.001	5.4089	0.0254
EW2B	10	0.002	0.000		
{A x V}	2	0.000	0.000	0.6404	0.5513
EW12B	10	0.003	0.000		
W	30	0.010			
TSQ/N=	32.4425	N= 36	SST=	0.0158	

homogeneous and heterogeneous control dynamics conditions are presented in Table 7.8. First and zero order control auditory tracking linearity R_{max} values are represented in the table for each individual subject, as the control dynamics in the visual tracking loop were selectively raised from zero to first and to second order. These average R_{max} values were then submitted to a two-way repeated measures analysis of variance. A summary ANOVA table is presented in Table 7.9. These data, averaged over subjects, are plotted as a function of order of controlled element dynamics in the visual tracking loop in Figure 7.4.

Auditory tracking linearity did not decrease significantly as the order of control was raised to first order. This is indicated by the statistically nonsignificant auditory order of control main effect in Table 7.9. There was no statistically significant decrement in tracking linearity as the auditory control dynamics were increased from zero to first order. Auditory tracking linearity, on the other hand, was found to vary significantly with the order of controlled element dynamics in the visual tracking loop. The main effect of visual order of control on auditory tracking linearity can be seen to be present for the majority of subjects in Table 7.8. We note from the table that when subjects performed auditory tracking with zero order control dynamics, tracking linearity decreased in five subjects out of six as the controlled element dynamics in the visual loop were increased from zero, to first, and to second order.

As with visual tracking, we note that the main effect on auditory tracking performance of introducing varying degrees of heterogeneity in controlled element dynamics between the tracking loops in multiple single loop control, is to reduce the overall tracking accuracy with which the tracking tasks can be performed. This effect is reflected in an overall increase in tracking NMSE, which may be attributable to an increase in the average amplitude of tracking remnant, or to a loss in the amount of information transmitted.

Analysis of Average Tracking Response delay τ Measures.

Visual Tracking

Average tracking response delay (τ) measures, computed over trials, for zero, first and second order control dynamics in the various homogeneous and heterogeneous control dynamics conditions, and for each subject separately, are presented in Table 7.10. These mean τ values were submitted to a two-way repeated measures analysis of variance. Both the effect of order of control dynamics in the visual tracking loop on average visual response delay, and that of order of control in the auditory tracking loop were examined.

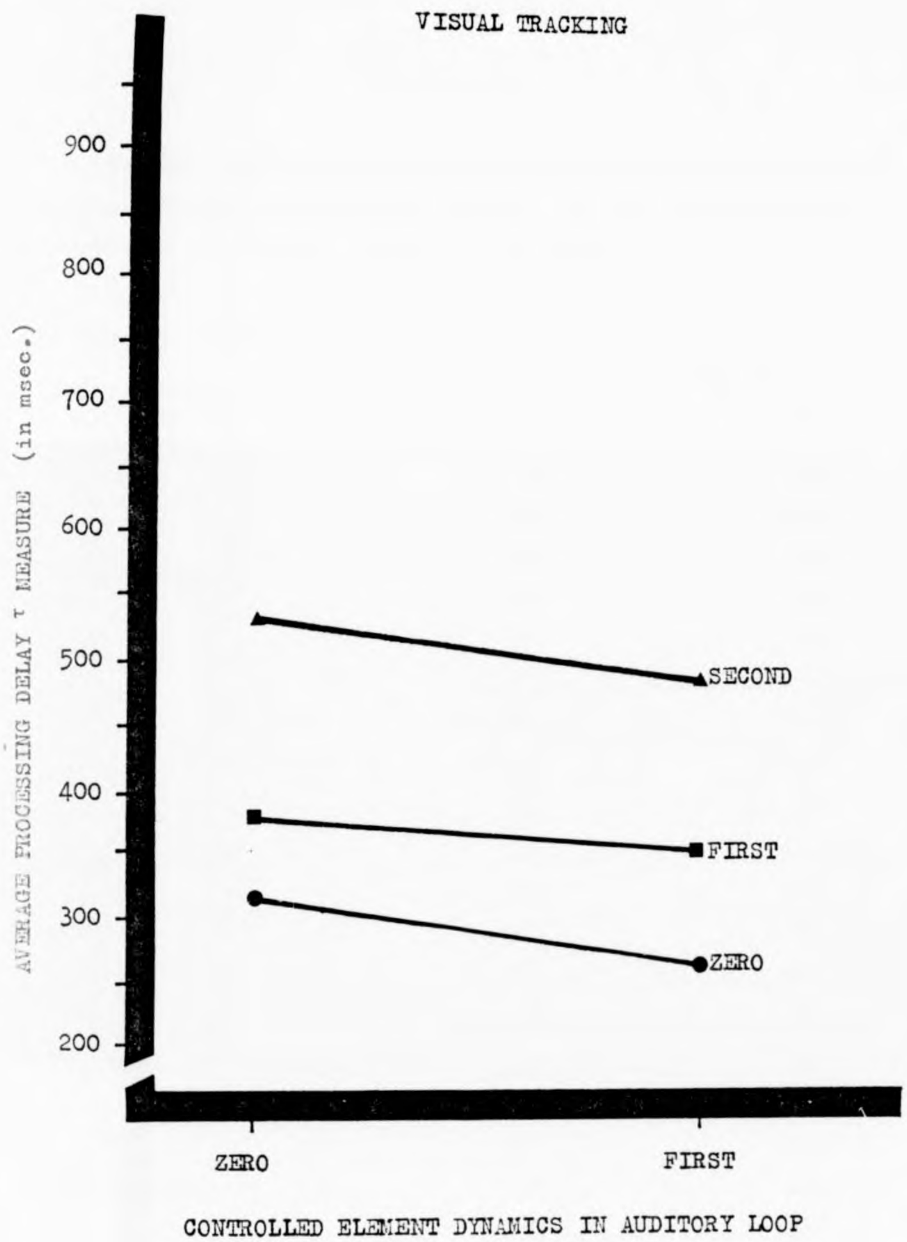

Fig. 7.5.- Average processing delay τ measure as a function of control dynamics in the auditory loop. Homogeneous .49 rad/sec inputs

TABLE 7.10

Average visual tracking response delay, τ (in msec), as a function of controlled element dynamics in both tracking loops. Homogeneous .49 rad/sec inputs. Experiment 4.

VISUAL TRACKING CONTROL DYNAMICS	S	AUDITORY TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE
PROPORTIONAL	1	258	183
	2	267	275
	3	325	300
	4	250	200
	5	300	300
	6	475	333
		$\bar{X}$= 313	265
RATE	1	292	242
	2	360	300
	3	325	413
	4	383	309
	5	350	350
	6	525	525
		$\bar{X}$= 373	357
ACCELERATION	1	383	592
	2	383	508
	3	1075	475
	4	442	438
	5	370	308
	6	550	575
		$\bar{X}$= 534	483

Average of 6 trials per cell.

TABLE 7.11

Summary ANOVA table of average visual tracking response delay, τ, measures, in Experiment 4.

SOURCE	DF	SS	MS	F	PROB
Subjects	5	197559.000			
Control Order {V}	2	298132.500	149066.250	10.2057	0.0040
EW1B	10	146061.500	14606.150		
Control Order {A}	1	13110.500	13110.500	1.5363	0.2702
EW2B	5	42668.000	8533.600		
{V x A}	2	2233.500	1116.750	0.0627	0.9393
EW12B	10	178032.500	17803.250		
W	30	680238.500			

TSQ/N= 5397103.5000 N= 36 SST= 877797.5000

These data are plotted as a function of order of controlled element dynamics in the auditory tracking loop in Figure 7.5. Examination of Table 7.11 reveals that only the visual order of control main effect was significant. τ was found to increase from 288 msec, to 362 msec and to 508 msec as the visual tracking controlled element dynamics were raised from zero, to first, and to second order. However τ did not vary significantly as a function of the order of controlled element dynamics in the auditory tracking loop.

If we turn to Figure 7.5 we note that the highest τ value in the graph corresponds to the heterogeneous second order visual/zero order auditory,control dynamics tracking condition. We note too that average τ decreased by some 51 msec when the controlled element dynamics in the auditory tracking loop were raised from zero order to first order, thus reducing the heterogeneity in control dynamics between the tracking loops. This represents a statistically nonsignificant reduction in τ of approximately 10%. When subjects performed visual tracking with first order controlled element dynamics (represented by the central curve on the graph) we note a small (16 msec) increase in τ as the controlled element dynamics in the auditory tracking loop were reduced from first order to zero order. This result is consistent with the notion that the degree of heterogeneity in control dynamics between the visual and auditory tracking loops determined the magnitude of average tracking response delay associated with the performance of each task. Looking at the lowest curve in the graph we note, however, a different result. Average tracking response delay in the heterogeneous,zero order visual and first order auditory control dynamics conditions is actually some 47 msec less than the overall τ value observed in the zero order homogeneous control dynamics condition. We note from Table 7.10 that this trend is present in four subjects out of six, with one subject deviating in an opposite direction by only 9 msec. Before dismissing this anomalous result as due to sampling error, the possibility of an order of control carry over effect from Experiment 3 remains. Recall that in Experiment 3 subjects worked at all times with homogeneous first order controlled element dynamics. If this previous experience in tracking with first order controls carried over to this experiment, it is conceivable that it would have produced a similar anomalous effect on auditory tracking response delay. If we turn to Figure 7.6,where average auditory τ values in both the homogeneous and heterogeneous control dynamics conditions are represented,we note the same anomalous effect when subjects performed visual and auditory tracking with zero order control dynamics in each loop. We note that the average τ value in this condition is some 91 msec greater than that observed when subjects performed the zero order auditory and first order visual tracking tasks concurrently. Support for the notion of a first order control dynamics carry over effect,comes from a further observation . When magnitude of average tracking response delay associated with the performance of each task. Looking at the lowest curve in the graph we note, however, a different result. Average tracking response delay in the heterogeneous,zero order visual and first order auditory control dynamics conditions is actually some 47 msec less than the overall τ value observed in the zero order homogeneous control dynamics condition. We note from Table 7.10 that this trend is present in four subjects out of six, with one subject deviating in an opposite direction by only 9 msec. Before dismissing this anomalous result as due to sampling error, the possibility of an order of control carry over effect from Experiment 3 remains. Recall that in Experiment 3 subjects worked at all times with homogeneous first order controlled element dynamics. If this previous experience in tracking with first order controls carried over to this experiment, it is conceivable that it would have produced a similar anomalous effect on auditory tracking response delay. If we turn to Figure 7.6,where average auditory τ values in both the homogeneous and heterogeneous control dynamics conditions are represented,we note the same anomalous effect when subjects performed visual and auditory tracking with zero order control dynamics in each loop. We note that the average τ value in this condition is some 91 msec greater than that observed when subjects performed the zero order auditory and first order visual tracking tasks concurrently. Support for the notion of a first order control dynamics carry over effect,comes from a further observation . When subjects performed visual and auditory tracking with homogeneous control dynamics in each tracking loop the visual and auditory τ values for zero order control were 313 msec and 464 msec respectively. Those for homogeneous first order control dynamics were, in turn, 357 msec and 461 msec for the visual and auditory tracking tasks respectively. When first order control dynamics were introduced in the visual tracking loop, and the auditory tracking control dynamics were zero order, auditory tracking τ reduced to 373 msec. Whereas, when the auditory tracking controlled element dynamics were raised to first order while those in the visual tracking loop remained at zero order, auditory tracking τ values increased to 566 msec. Apparently, auditory tracking with zero order control dynamics led to a decrease in average response delay when first order, but not zero order, control dynamics were introduced in the visual tracking loop. In similar fashion, visual tracking τ with zero order control dynamics actually showed a reduction from 313 msec, for homogeneous zero order controls, to 265 msec when the auditory tracking controlled element dynamics were raised to first order. Though small in magnitude, these effects do hint the presence of a small carry over effect from Experiment 3.

Auditory Tracking

Average auditory tracking response delay τ measures, computed over trial replications, for each subject individually,

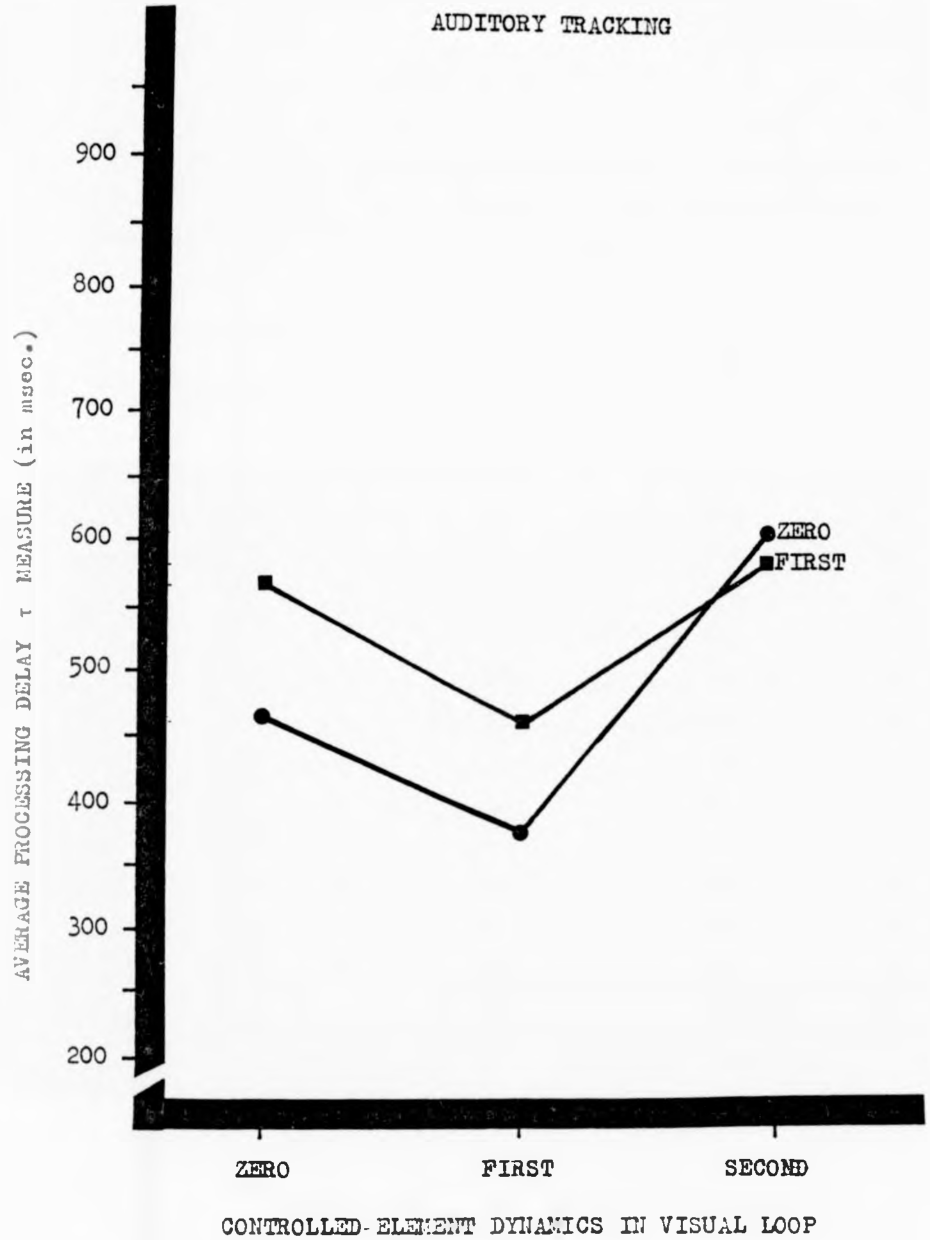

Fig. 7.6.-Average processing delay τ measure as a function of control dynamics in the visual loop.Homogeneous .49 rad/sec inputs.

TABLE 7.12

Average auditory tracking response delay, τ (in msec), as a function of controlled element dynamics in both tracking loops. Homogeneous .49 rad/sec inputs. Experiment 4.

AUDITORY TRACKING CONTROL DYNAMICS	S	VISUAL TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE	ACCELERATION
PROPORTIONAL	1	360	283	700
	2	600	600	867
	3	392	300	400
	4	367	342	633
	5	700	413	570
	6	363	300	442
		$\bar{X}$= 464	373	602
RATE	1	517	408	375
	2	692	613	667
	3	533	325	666
	4	438	420	563
	5	767	550	667
	6	450	450	567
		$\bar{X}$= 566	461	584

Average of 6 trials per cell.

TABLE 7.13

Summary ANOVA table of average auditory tracking response delay τ, measures, in Experiment 4.

SOURCE	DF	SS	MS	F	PROB
Subjects	5	337279.000			
Control Order {A}	1	29814.000	29814.000	3.6286	0.1136
EW1B	5	41082.000	8216.400		
Control Order {V}	2	186812.000	93406.000	13.7655	0.0015
EW2B	10	67855.000	6785.500		
{A x V}	2	25891.000	12945.500	1.3875	0.2941
EW12B	10	93303.000	9330.300		
W	30	444757.000			

TSQ/N= 9302500.0000 N= 36 SST= 782036.0000

in the various homogeneous and heterogeneous controlled element dynamic conditions are presented in Table 7.12. These data were then submitted to a two-way repeated measures analysis of variance. A summary ANOVA table is presented in Table 7.13. Average auditory τ values, computed over subjects, for zero and first order controlled element dynamics are plotted as a function of visual order of control in Figure 7.6.

Examination of Table 7.13, reveals that only the visual tracking order of control main effect was significant. Overall, zero order control auditory tracking average response delays were shorter than comparable delays obtained when tracking with first order control dynamics. These values were 480 msec and 537 msec respectively. Average τ values were found to vary significantly, however, with the order of controlled element dynamics in the visual tracking loop. When subjects performed the visual and auditory tracking tasks with homogeneous zero order control dynamics, average auditory tracking response delay τ measures were greater than those observed when the control dynamics in the visual tracking loop were raised to first order. This effect was not statistically significant and may be attributed to the suspected first order carry over effect from Experiment 3. Auditory τ values, however, were found to increase significantly when the controlled element dynamics in the visual loop were raised to second order. The increase from 464 msec to 602 msec represents a 30% relative increase in τ relative to the homogeneous zero order control dynamics condition when the visual and auditory tasks were performed with homogeneous first order control dynamics. Average auditory τ values were found to be considerably lower than those observed when the control dynamics in the visual loop were reduced to zero order, or raised to second order. These contrasts were not statistically significant, but the difference between first order auditory / second order visual, and the homogeneous zero order condition approached significance. Examination of Table 7.12 reveals these effects to be fairly well represented between subjects.

Correlation Between the Absolute Tracking Error Signals $e_v(t)$ and $e_a(t)$.

The average correlation values, r , relating the absolute tracking error signals $e_v(t)$ and $e_a(t)$, were computed over trials, for each subject separately, in the various homogeneous and heterogeneous conditions. These values are presented in Table 7.14. Since each correlation coefficient was computed over 512 sampled data pairs, a value of r beyond the range ±.087 may be considered significant at the .05 level. Examination of Table 7.14 reveals no significant r values in the various tracking conditions. Individual subject data do not suggest any evidence of a trend toward significant high negative correlation between the

TABLE 7.14

Average correlation values, r, between the absolute tracking error signals with homogeneous, and heterogeneous, control dynamics between the loops. Experiment 4.

VISUAL TRACKING CONTROL DYNAMICS	S	AUDITORY TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE
PROPORTIONAL	1	.001	.110
	2	-.003	-.001
	3	-.023	-.021
	4	.116	-.014
	5	.150	.131
	6	.047	.108
		$\bar{X}$= .048	.052
RATE	1	.088	.103
	2	.050	.043
	3	.122	.091
	4	.075	-.054
	5	-.007	.091
	6	.041	-.063
		$\bar{X}$= .062	.035
ACCELERATION	1	.028	.142
	2	-.156	.061
	3	.252	.242
	4	.032	.030
	5	.010	.066
	6	.082	-.081
		$\bar{X}$= .041	.077

Average of 6 trials per cell.

absolute tracking error signals as the degree of heterogeneity in controlled element dynamics was increased. There were some scattered, significant but low r values in the various tracking conditions, but these values tended to be positive rather than negative. In particular, we note three of these values occurred when subject 3 performed visual and auditory tracking with heterogeneous controlled element dynamics. This, in turn, suggests that this subject may have found these conditions most taxing, especially those involving second order control, and may have on occasion allowed tracking error to increase in both loops simultaneously before taking appropriate corrective action. Indeed, if we turn to Table 7.2, we note that this subject has the highest overall visual tracking NMSE values when second order control dynamics were introduced in the visual tracking loop.

These results therefore do not provide any evidence in support of the notion that when subjects must reduce tracking error in both tracking loops simultaneously, they may only perform these tasks serially. In effect, it would appear that subjects were capable of processing visual and auditory information from both tracking loops simultaneously. They were able to reduce received tracking error in one tracking loop irrespective of the magnitude of tracking error in the other loop. Although, subject 3 may be considered an exception, perhaps this subject's data do suggest that at some point, perhaps when the tasks became very difficult to perform, tracking error in one loop may have on occasion increased with increasing tracking error in the other loop. We should note, however, that subject 2 actually showed a small, though significant, negative correlation between the absolute tracking error signals in the second order visual and zero order auditory tracking control dynamics condition. This condition was generally agreed to be the most difficult to perform.

Test of Linear Crosscoupling Between the Subject's Control Command Signals $c_v(t)$ and $c_a(t)$.

In order to determine whether any linear crosscoupling was present between the tracking loops, in the various conditions, the correlation coefficient relating the subject's control command response signals $c_v(t)$ and $c_a(t)$ was computed separately on each trial. Average values were then computed over trials, and are presented for each subject individually in Table 7.15. Only those correlation values in the table exceeding the range $\pm.084$ may be considered significant at the .05 level. Overall, we note very little consistency either between subjects or between conditions. Noteworthy, however, is a cluster of negative correlation coefficients in the heterogeneous zero order visual/first order auditory control dynamics condition. The origin of the high negative correlation coefficient observed for subject 5 is unknown, but it could suggest linear crosscoupling such as that reported for homogeneous control dynamics by Van Lunteren (1977). No such linear, inverse,

TABLE 7. 15

Average correlation coefficient between the operator's control command movement signals $c_v(t)$ and $c_a(t)$ when tracking with homogeneous and heterogeneous control dynamics. Experiment 4.

VISUAL TRACKING CONTROL DYNAMICS	S	AUDITORY TRACKING CONTROL DYNAMICS PROPORTIONAL	RATE
PROPORTIONAL	1	.072	-.046
	2	.082	-.037
	3	.022	-.027
	4	.076	-.297
	5	.144	-.404
	6	-.009	-.134
		$\bar{X}=$ .065	-.158
RATE	1	-.179	.063
	2	.247	.100
	3	-.058	-.023
	4	-.064	-.003
	5	.026	.183
	6	.153	-.292
		$\bar{X}=$ .021	.005
ACCELERATION	1	.072	.110
	2	.062	.042
	3	.052	.050
	4	.164	.153
	5	.132	.153
	6	.100	-.015
		$\bar{X}=$ .097	.081

Average of 6 trials per cell.

crosscoupling was noted, however, between the tracking loops in either the zero order or first order, homogeneous control dynamics conditions.

It would not seem, therefore, that linear crosscoupling between the loops, reflecting perhaps some form of response interference, was a major factor in producing the observed task interference effects. In particular it cannot account for those directly attributable to the selective variation of heterogeneity in controlled element dynamics between the visual and auditory tracking loops.

DISCUSSION

The results obtained in this experiment corroborate in part those of Experiments 2 and 3. Visual and auditory tracking NMSE was found to increase with increasing control dynamics order. Moreover, visual and auditory tracking task performance was found to depend not only on the order of control dynamics in any given loop, but also on the degree of heterogeneity in control dynamics between the loops. There was, however, evidence indicating that for very low input signal bandwidths and for well practised subjects, zero and first order heterogeneity in control dynamics between the tracking loops, did not produce significant changes in visual and auditory tracking NMSE. When the control dynamics in visual tracking loop were raised to second order, however, significant increases in auditory tracking NMSE were observed. This result suggests, along with those obtained in Experiment 3, that the quality of performance of a continuous information processing task depends on the information processing demands imposed by another task performed concurrently with it. This, in turn, suggests that the controller of a multiple single loop compensatory tracking system may not in general behave as a true parallel information processing system, because of central information processing limitations which produce interference between the tasks. This is not to deny the possibility that more peripheral factors, such as response interference, were mediating the observed task performance interactions. We can dispense with within-modality, interference effects, because tracking error information in each tracking loop was presented to a different sensory modality. The contribution of response interference factors may not be so easily dismissed. We note, however, that although response interference factors, albeit non statistically significant ones, were observed both in Experiments 1 and 2 in the VICOPY and AUCOPY tracking conditions, the effects were never as great as those observed when subjects performed the visual and auditory tracking tasks simultaneously. If we examine the tracking NMSE values obtained when subjects performed the homogeneous inputs and homogeneous control dynamics conditions in the various experiments, we observe that when proper comparisons are made, increases in either the bandwidth of the forcing functions, or of the order of control dynamics produced corresponding increases in both visual and auditory tracking NMSE. These effects were considerably greater than those observed in the VICOPY and AUCOPY tracking conditions. Hence, response interference effects might well have been present in this, and in the previous experiment. It is, however, unlikely that response interference effects alone produced the pattern of results observed in these experiments. Moreover, an examination of the linear correlation between the subject's control command signals $c_v(t)$ and $c_a(t)$, did not reveal consistent effects, either between, or within, subjects in tracking conditions that would indicate an obvious linear crosscoupling between the tracking loops. Nevertheless, isolated instances in which the correlation coefficient relating the control command signals was significant were noted. In particular, when the visual tracking task with zero order control dynamics was performed concurrently with a first order auditory tracking task. No such pattern of results was found, however, when the visual tracking task was first order, and the auditory was zero order. Why this should have been so is not clear.

The finding that the performance of one of two given visual and auditory tracking tasks performed concurrently depends on the relative attentional demands for processing capacity set by either task, is not consistent with a notion that attentional resources are allocated in fixed amounts to meet fixed attentional demands inherent in the tasks. Nor for that matter is it entirely consistent with undifferentiated capacity models such as those proposed by Moray (1967) and Kahneman (1973). This is because these models imply that interference between concurrently performed tasks arise when the cumulative capacity demands by the tasks exceed the total available capacity. Provided the total capacity is not exceeded, these models readily accommodate simultaneous, interference-free, multiple task performance.

In this as in the previous experiments, there was no evidence of serial switching between the tracking loops in multiple single-loop control. The absence of consistent negative correlation between the absolute tracking error signals in each tracking loop is not supportive of either serial single-input, or of single-response, information processing models of human attention.

CHAPTER 8

GENERAL DISCUSSION

Taken in conjunction, the results of the four experiments conducted in this research permit the following general observations.

When subjects performed visual and auditory tracking tasks separately, they were able to perform them with considerably less error than when they performed them in conjunction.

The requirement to respond using both hands, as in the VICOPY and AUCOPY tracking conditions, did not generally lead to a significant decrement in task performance. Although response interference was evidently present in these tasks, the effects were considerably smaller than those observed in time-shared, bimodal compensatory tracking conditions.

Selective variation of either forcing function input signal bandwidth or order of controlled element dynamics, produced corresponding decrements in both visual and auditory tracking conditions. Time-shared tracking effects were found to occur independently of experimental manipulation of either of these two variables.

Time-shared tracking decrements in task performance, indicated by increases in overall tracking error (NMSE) were found to arise from (1) decrements in tracking linearity, (2) average response delay, or (3) from the interplay between these two parameters.

Whether the forcing function input signals, in multiple single-loop control, were identical or unrelated, made no significant difference to either visual or auditory task performance. Yet there were some strong hints of a facilitation in tracking when subjects performed the BOSAME tracking tasks. It would appear, however, that the subjects were not taking obvious advantage of correlation between the forcing functions but rather dealt with the input signals separately.

There was no consistent or reliable evidence of serial alternation in task performance in multiple single-loop control. Analysis of absolute tracking error between the tracking loops did not reveal any evidence of a relation between the error signals, It would appear that the subjects were processing information from the displayed tracking error signals in parallel. Hence, the reduction of error in one loop did not depend to any great extent on the amplitude of tracking error occurring simultaneously in the other tracking loop.

When subjects performed the visual and auditory tracking tasks concurrently, the performance of both tasks was found to decrease as a function of selective variation of either the forcing function input signal bandwidth, or order of controlled element dynamics in either one, or both tasks.

Overall, visual tracking performance was considerably better than auditory tracking performance. This discrepancy in performance between the visual and auditory tracking tasks was often attributable to relatively greater average response delays in auditory tracking. Auditory tracking linearity, however, was often as high as that observed in the visual tracking task.

Some of the implications of these findings are straightforward; some others are not. For example, although increases in τ accompanying the requirement to divide attention between continuous visual and auditory tracking tasks are consistent with single-input, serial, information processing theories of attention, there may be other reasons unrelated to the switching of attention per se which could produce such an effect (see p.56 for a discussion). Such a finding, however, need not be worrisome to a parallel information processing model of man's attentional process. Along with Cliff's (1971) study, in which continuous visual tracking was performed concurrently with auditory shadowing, the results of experiments 1 and 2 also revealed significant time-sharing increases in τ, yet in the literature of time-shared tracking, performance (e.g. Baty, 1972, Levison, Elkind and Ward, 1971, Allen, Clement and Jex, 1970; Wickens, 1976), the majority of studies which have involved frequency domain analysis of tracking data have observed no such increases in τ. A notable exception (involving highly practised subjects) is provided by Watson's (1972) study, cited earlier. Watson observed a very slight increase in the visual tracking response lag parameter of the operator when an additional visual information processing task was introduced. This increase in phase lag was significant at about one third of the signal frequencies measured. One would like to know whether the usual absence of a time-sharing effect on τ, when frequency domain and not time domain analysis of time-shared tracking performance is used, arises from differences in analytical methodology, rather than from between-experiment variability. Poulton (1974, p. 134) has pointed out that the effective time delay parameter, τ, in the system open-loop transfer function is not the operator's transmission time lag, or his processing delay. Rather, τ represents the residual time lag after the linear components of the subject's tracking control command signal have been processed by high pass and low pass filters. Thus, if the estimated τ parameter does not in effect represent the human's average tracking response delay parameter (see Poulton, 1974) Chapter 4, p. 43, for a more detailed discussion), where the margin of error can be as high as 86%, it is conceivable that the open-loop transfer function technique may not be sufficiently sensitive to detect changes in τ with time-sharing.

It might be possible to incorporate time-sharing changes in τ within the framework of a general, parallel, information processing model of human attention and performance if we consider an interplay between changes in τ and tracking linearity which allows the development of optimal strategies by the operator. The results obtained in Experiments 3 and 4 which showed that the performance of a given tracking task, in multiple single-loop control, depends on the attentional information processing demands made by another task performed concurrently with it, may not support either differentiated or undifferentiated capacity models of attention. This is because in the first instance, differentiated capacity models of attention predict no such task performance interactions, unless of course, capacity limitations are exceeded. Undifferentiated capacity theories (Kahneman, 1973, Moray, 1967), on the other hand, can accommodate such results but only by assuming as well (1) that the combined task demands for processing capacity exceed the total capacity available, or (2) structural interference was producing the observed multitask interference effects. It has already been argued in Chapter 7, however, that (1) neither the tasks as a whole seemed so difficult to carry out simultaneously that total capacity limitations could be thought to be exceeded (not when observed tracking performance was so high), nor (2) that the requirement to respond with both hands could account entirely for the observed time-shared visual and auditory tracking effects.

Yet, even if the notion that information processing attentional resources are allocated freely to the various tasks is questionable, the results of these experiments are consistent with a general undifferentiated capacity model. That is, some, but not all, information processing resources can be allocated by the brain in a rational, flexible, and perhaps optimal manner. In other words, the number of attentional resources allocated to a given information processing task is a weighted function of the information processing content of other unrelated activities the human may concurrently perform. Such an attention allocating process, or allocation policy, would imply that the amount of attention allocated to a given task is determined in relative terms. The amount of information processing resources that may be allocated to a given source of information is a function of the content of other distinct sources that coexist with it at any one moment. If the rate of information associated with the processing of a given signal source were suddenly to increase, such a process would also imply that the amount of attention that could be allocated to it, and to any other concurrent source of information,would always be less than that which would be allocated to any one of the sources if it occurred by itself. Such an undifferentiated capacity, attention allocation process, or mechanism, carries with it the obvious advantage that if a high information content signal should occur at any one moment, the amount of attention allocated to other relatively less informative sources would be diminished to accommodate the change in the total rate of incoming information. The results of Experiments 3 and 4 do indicate, although for very low forcing function input signal bandwidths, that when the information content of a given task is increased relative to another task performed concurrently and high performance in both tasks is a premium, then <u>both</u> tasks show a decrement in performance. It would appear, therefore, that the amount of attention allocated to the tasks was determined in relative, <u>reciprocal</u>, terms quite independently of the total amount of attentional resources potentially available. Hence, it should be possible to show that the amount of attentional resources allocated to any given source of information depends on momentary similar demands made by other sources. One could conceive of a mechanism incorporating such properties, where some finite amount of resources are allocated to processing various inputs so as to keep the amount of incoming information more or less optimal. At a first level of approximation, a priority system could be incorporated so that the source of information conveying the most information would be allocated most resources, at a distinct cost in the reduction of attention allocated to other concurrent sources. Hence, the concurrent performance of two distinct information processing tasks might perhaps always be found to show a decrement of overall task performance relative to the single performance of either task. This, of course, would only be the case if the tasks were to convey as much information separately as in dual-task combination, and, furthermore, if the performance measures used were sufficiently sensitive to detect such time sharing decrements for very low rates of task-related input information.

We do not at present have enough evidence to enable precise mathematical modelling of the allocation policy. Extension of the results obtained in Experiments 3 and 4 with a greater range of input signal bandwidth may allow the development of a model of attention allocation process in time-shared continuous information processing. It should be pointed out, however, that whether consciousness is or is not implied, is of little consequence to this problem. There is good evidence, cited earlier, which suggests subjects who are explicitly instructed to give highest priority to one of two concurrently performed information processing tasks may nevertheless show time-sharing decrements in the performance of the task.

An elaboration of the undifferentiated capacity hypothesis to incorporate relative, instead of free, allocation of attentional resources to a given source of information, may in effect rescue the theory from premature dismissal. For instance, Sanders (in press), discussing the implications of the major theoretical models of attention thus far proposed (within the context of a theory of performance and workload) concludes against both Moray's (1967) and Kahneman's (1973) undifferentiated capacity models. Whether, or not, the view that attentional resources are allocated freely to the various tasks concurrently performed is correct, is a very different issue from that relating specifically to an undifferentiated capacity principle whereby attentional information processing, resources (units, skills, plans, algorithms, schemas, etc.) may be flexibly allocated to various tasks. Kahneman (1973, p. 199) did acknowledge that notions such as free allocation of resources and capacity interference may not readily incorporate evidence of task performance interaction. Hence, in order to accommodate such findings, Kahneman invoked the notion of structural interference (see also Allport, Antonis and Reynolds, 1972). Yet, before dismissing undifferentiated capacity notions, it is important to consider the evidence against undifferentiated capacity theories of attention advanced by Sanders. He cited two widely quoted, yet most questionable, sets of results. One concerns the results obtained in multiple-input, multimodal, experiments conducted by Shiffrin (1975). The other concerns the results of 'probe RT' experiments by Posner and Klein (1973).

Consider first the tasks used by Shiffrin and his interpretation of the results. Here we turn to Boulter (1977) who has spotted a crucial flaw in logic in the Shiffrin studies. In Shiffrin's experiments, subjects were presented with various types of near-threshold signals. These signals could either be visual, auditory, or tactual. The procedure involved presenting three observation intervals per trial (one per modality) either in succession or in synchrony. But one of the signals was always presented on any one trial. Shiffrin reasoned thus: if successive intervals always occurred in the same order, and, furthermore, if a given subject is capable of attending selectively to any one sensory modality, successive, single-input, expected signal conditions would be more likely to yield a greater number of correct detections than conditions in which two or more stimuli were presented in synchrony. The results showed no decrement in signal detection performance when either one, or two, or three sensory modalities were stimulated in concert. In fact, performance in the simultaneous condition has on occasion been found superior. The results are obvious and replicable, but alas the logic is not. As Boulter points out, "the confounding factor is that, in effect, their observer's task is to detect, for example, a visual signal, but to conclude that a visual <u>and not</u> an auditory, or tactile, signal has occurred" (Boulter, 1977, p.387,his italics). Hence, if the subject attends to the three modalities in parallel as he ought to, when only one signal is presented he must reject two, no-evidence, alternatives, and accept one with evidence from the incoming signal. When two signals are presented, he rejects one, no-evidence, alternative and accepts evidence for the other two. When the three signals are presented, no such rejection is necessary, but three affirmative decisions must be made. Unless one assumes that the time taken to decide "no-evidence", or "evidence", are different (and perhaps they are since on occasion subjects have been found quicker in responding in the simultaneous input conditions), the mean reaction-time comparison between the presumed single-task condition and time-sharing condition is vacuous because the tasks set fail to meet the criteria of a valid time-sharing paradigm.

Consider next the Posner and Klein (1973) "Probe RT" results considered by Sanders as evidence to reject the undifferentiated capacity hypothesis. In the probe RT paradigm the subject already occupied in performing a given task is asked to respond by pressing a button to a probe stimulus usually presented to another sensory modality. The presentation of the probe stimulus can be timed to occur at various phases during the performance of the task. The longer the time taken to respond to the probe, the more capacity demanding the specific task performance phase in question is thought to be. Posner and Klein

(1973), for instance, found that if subjects are to judge two letters presented visually in succession as 'same' or 'different' and whilst doing so an auditory probe is presented during either presentation of the first letter, between letters, or during presentation of the last letter, mean reaction time to the probe does not increase for the first letter, but does for the interval, and increases even more when it is presented with the second letter. One serious drawback to drawing firm conclusions from probe RT data such as these, is that if a visual probe stimulus is used instead, a rather different pattern of results arises (Schwartz, 1976). Moreover, as McLeod (1978) has recently shown, if the modality of response to the probe is changed from manual to verbal, again a considerably different pattern of results is obtained. Hence, neither the results observed by Shiffrin (1975) nor those observed by Posner's probe RT methodology can be used as evidence either to dismiss or to support differentiated capacity multiprocessor models such as those advocated by Allport, Antonis and Reynolds (1972).

Phillips and Christie (1977), following a suggestion by this author to incorporate a between modality presentation condition in their research (in order to determine whether previously observed visual memory interference effects were of central rather than peripheral origin), and extending the findings of pilot research conducted in conjunction with him, obtained quite decisive evidence which creates difficulties for such models. Phillips and Christie both questioned and tested the widely acknowledged notion that visualizing and seeing interfere with each other because these information processing activities compete for special purpose visual processing resources (Brooks, 1967, 1968). They found that although a distracting task of adding five sequentially presented digits interfered with active visualization of random patterns, and the requirement to simply read them did not so interfere, these results held true even when the digits were presented auditorily. Presumably, interference with active visualization was not tied in any obvious way to the visual modality. Moreover, since only one task involved mental arithmetic, it would be unlikely that interference was due to rivalry for special purpose,mental arithmetic,processing units. These results were replicated in a second experiment in which vocalization was suppressed (pilot work had revealed that auditory shadowing of the digits interfered more with visualization than reading them) and interference due to vocal responding effects minimized. The general pattern of results that emerged from these and other related experiments led these researchers to conclude that the process of visualization places demands on central, general purpose, information processing resources. One shortcoming in this study, however, is that interference effects arising from visualization of the digits during mental arithmetic were not controlled.

Indeed, although not statistically significant, auditory presentation of the digits to be added actually showed a relative decrement of 6% correct pattern recognition performance with respect to visual presentation. If some numerical visualization during mental addition was occurring, and this in turn was greater when auditory input was involved, one might not entirely dismiss this factor as underlying the observed effects. Yet, as these researchers pointed out, if it were true that adding auditorily presented digits involved the visual modality, it would in effect reduce the grounds for calling the visual processor involved "special purpose" (Phillips and Christie, 1977, p. 648 line 34, their quotation marks).

We will recall that the existence of more or less peripheral, permanent, information processing structures that may or may not require attention, and which may be imbued with some form of sensory memory, is not denied by undifferentiated capacity theories. Indeed, the notion of attention as an undifferentiated but limited-capacity information processing system where a more or less optimal attentional allocation resources policy modulates, or guides, the flow of information into these structures, may not be entirely at odds with multi-processor theories of attention. One of the functions of attention could very well be to ensure appropriate input to more or less permanent structures such as the neural networks envisaged by Pitts and McCulloch (1947), Hebb (1949) and Bindra (1976). The increases in response variability, or remnant, associated with the requirement to time-share attention observed in this, as in other studies, is certainly consistent with this notion.

Mechanisms of synaptic inhibition have long been thought to mediate the establishment and maintenance of an 'optimal level of cortical tone' (Pavlov, 1949a), whereby, as Luria lucidly pointed out, optimal waking conditions can be maintained so "that man can receive and analyze information, that the necessary selective systems of connections can be called to mind, his activity programmed, and the course of his mental processes checked, his mistakes corrected, and his activity kept to the proper course. It is well known that such precise regulation of mental processes is impossible during sleep; the course of reminiscences and associations which spring up is disorganized in character and, properly directed mental activity is impossible" (Luria, 1973, p.44). Mechanisms of synaptic inhibition such as those envisaged by Pavlov, (1949a: see also Thomson and Bettinger, 1970, and Walley and Weiden, 1973), suggest means whereby appropriate modulation of input to various structures may be achieved, by appropriate alteration of signal to noise ratios along neural channels. Perhaps the greatest wealth of insight into this notion is given by Luria (1973, p. 44 - 45 and 197 - 199) suggesting how conjectures and studies of attention may converge on neuropsychological knowledge. If it should be found that a relationship exists between observed cortical tone dynamics, and optimal allocation of attention, new vistas for dialogue between researchers studying attention from information processing and neuropsychological disciplines would appear. Some rapproachement between these disciplines, for example, is explicit in conceptions such as Morton's (1969) 'logogen' and Shallice's (1972) 'activating' systems. Both theories, in fact, imply that the activation of any particular unit is determined by a given input signal in the context of background noise. Thus our ability,or skill, in maintaining optimal cortical tone may be shown to relate to our ability to establish and maintain high levels of attentional performance. In this context, even though he appealed to a concept of arousal in drawing his conjectures and did not consider the full implications of Pavlov's fundamental neurodynamic laws, Kahneman's effort theory may well be considered and developed in this light. But it seems unlikely that his initial attempt to 'flow chart' man's attentional process with no revision of the allocation policy will be of much future use. Revised, however, to incorporate the principle that the amount of attention allocated to a given task is a weighted (at present unspecified) function concurrent information processing priorities, such an undifferentiated capacity theory may well be shown to provide a most powerful framework. In time, such a framework may provide cogent prediction in both neuropsychological and information processing terms, whereas at present, there is much description and unfortunately little or no accurate prediction concerning the dynamics of man's attentional process.

It is important to note, that unlike the undifferentiated capacity models advanced by Moray and by Kahneman, the undifferentiated capacity model proposed here postulates that the amount of information processing capacity, or effort, allocated to a given task is not determined simply by the difference between total and combined-task capacity demands. Rather, for all magnitudes of combined-task capacity demands, the amount of attention allocated to a given task (limited capacity assumed), is modulated dynamically in relation to the informational content of other irrelevant, more or less distracting, sources of information.

The advantage of such a regulatory system is obvious in that it enables the allocation of attention to relatively high information content signals as they arrive, inhibiting in relative terms the amount of capacity allocated to any one of the tasks concurrently performed without having to wait until capacity limitations are exceeded. Thus, for example, we might well carry out continuous information processing tasks such as the tracking tasks used here, while engaging simultaneously in daydreaming. If, however, the contents of the daydream suddenly become more interesting, or distracting, the performance of the tracking task will suffer as neglect of it sets in. But, since a decrement in tracking performance implies an increase in error signal information, the amount of attention allocated to the distracting daydreaming activity might be more or less reduced to restore the quality of tracking. Accordingly, Deutsch and Deutsch's (1963) initial conception of stimulus importance may well be seen to have some truth in this light. This is because quite independently of whether current capacity demands placed by simultaneous stimuli exceed capacity limitations, or not, the stimulus (or set of stimuli) which conveys most information to the subject, will also be the one receiving most attention. Thus, one important implication of this is that regardless of how 'important' a given incoming signal might be to the subject, the amount of attentional resources allocated to processing it would only be determined in relation to the 'importance' of other concurrent, distinct, information streams. Thus, we are led to a curious prediction. If an additional input signal is provided which also conveys relevant task-related information to the subject, it should be found that performance in this dual-input condition will actually <u>improve</u> performance of the given task. Such a result has been reported by Vinje and Pitkin (1972). These researchers found that visual compensatory tracking performance was improved if tracking error signal information was displayed simultaneously to the subject over headphones. On the contrary, the requirement to process information from two concurrent input signals over two distinct modalities did not have deterimental effects on subjects visual tracking task performance.

Since all information processing tasks are assumed to require attentional resources, if two concurrent streams of unrelated task-related information must receive attention simultaneously, then, by virtue of the allocation policy, there would always be relatively less attention allocated to each of the tasks. The performance of one of several concurrent information processing tasks would be less, relative to a full attention condition in which only one task need be performed. Hence, parallel information processing activity between two tasks is possible, but always at a distinct cost in task performance.

Note that the reasoning above applies only to processing of task-related information. If prolonged practice, or the involvement of memory, reduces the informational load associated with performing a given task, or tasks, then to show that practised subjects can perform complex information processing tasks simultaneously, with little or no interference, might simply mean that the tasks no longer conveyed as much information to the subject as when they were initially introduced. The important point, here, is of course, that with experience in performing a given task, memory may play a major part in reducing the information load associated with the performance of the task. We turn to Poulton (1957b) and to studies of simple sine wave tracking, which show clearly the involvement of memory in reducing task-related information. Whether consciousness plays any part in this seems to be immaterial. Pew (1974), for instance, showed that when subjects performed a visual tracking task involving an otherwise random input, and a segment of the forcing function was repeated over trials, while the segments before and after varied, this segment of the input signal was tracked considerably better than the other segments. Subjects, however, were unaware of this experimental manipulation. Thus the informational content of the signal of the 'familiar' segment appeared to be less than that of the other segments. This was so even though, in every other sense, the statistical features describing all the segments involved were the same. There is good reason to believe, therefore, that one of the functions of attention is to enable the establishment in memory of task descriptions, or plans, which when compared with the actual tasks they represent, reduce the amount of uncertainty associated with the performance of that (or of a very similar) task.

Task-related information, or task uncertainty, may then be conceived to be the magnitude of discrepancy, or mismatch, between the internal representation of the task and the actual task being performed. Support for this notion comes from the work by Locher and Kundel (see Monty and Senders, 1976, p. 349), and by Mooney (1958). Locher and Kundel report that trained radiologists can tell as much about a chest film shown for only 200 msec as they can after a very elaborate search of the film. The error rates for both conditions being comparable. In this sense, Mooney (1958) showed that people could recognize novel configurations as efficiently with only brief tachistoscopic exposures as with longer exposures in which active visual scanning was encouraged. Thus, in a very important sense, our ability to attend efficiently so as to coordinate and integrate our experience optimally, within information processing constraints, may be conceived to be one of the earliest skills (if not the earliest), we develop. By controlling and coordinating the flow of task-related information so as to enable the establishment in memory of an appropriate representation of the elements which comprise the task, we are in a sense liberated from having to process information about every aspect of a familiar task anew. It couldbe said of attention, therefore, that one of its main functions is to enable us to learn how to process information about more or less invariant aspects of daily activities so that we might be required to monitor only crucial mismatches between 'ideal' and actual task performance, leaving us free, but only in a relative sense, to engage in other, perhaps more uplifting and enjoyable, information processing activities.

we might be required to monitor only crucial mismatches between 'ideal' and actual task performance, leaving us free, but only in a relative sense, to engage in other, perhaps more uplifting and enjoyable, information processing activities.

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Technical Bulletin

Helipot® Model 3371
$1\frac{5}{16}$" DIAMETER SINGLE-TURN CONDUCTIVE PLASTIC POTENTIOMETER

APPENDIX A

Effective date: April, 1974

Helipot® Model 3371 precision potentiometer provides:

- Output smoothness 0.1% max.
- Essentially infinite resolution.
- Power rating of 1.0 watt at 65°C.
- Standard resistances from 1KΩ to 390KΩ.
- New, proprietary conductive plastic resistance element.
- Many spec features available at nominal increase in price.
- Total resistance change is 4% max. after 1,000 hours at rated power.
- Ideal solution to panel control applications requiring top performance at an economical price.

Model: 3371 bushing mount with metal sleeve bearing.

SPECIFICATIONS

Electrical

Standard resistance range, ohms	1,000 to 390,000
Standard resistance tolerance	±10%
Min. practical resistance tolerance	±5%
Independent linearity	±0.5%*
Min. practical independent linearity	±0.25%*
Power rating, watts	1.0 at 65°C derating to 0 at 105°C
Input voltage, max.	400V DC or within power rating
Dielectric strength	1,000V RMS
Insulation resistance	1,000 megΩ
Actual electrical travel, nominal	348°
Electrical continuity travel, min.	350°
Output smoothness, max.	0.1%
End voltage, max.	0.5% of E_{in}
Resolution	essentially infinite
Resistance temp. char., max.	4% (−25° to 105°C)

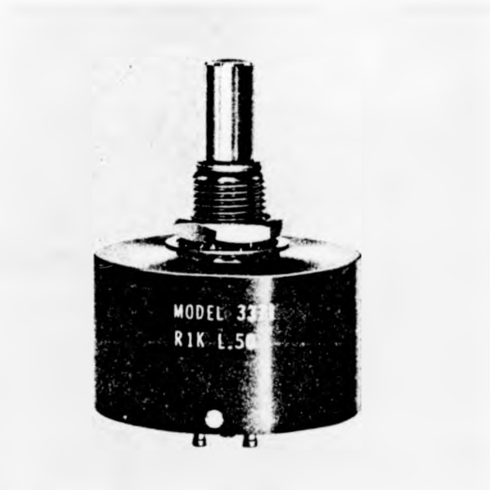
*Linearity is measured between 1.0% and 99.0% of the input voltage.

Mechanical

Number of turns	single-turn
Total mechanical travel	360° continuous (350° ±2° with stop)
Starting torque, max.	1.0 oz-in. (0,0071 N•m)
Running torque, max.	1.0 oz-in. (0,0071 N•m)
Shaft end play, max.	0.007" (0,1778 mm)
Shaft radial play, max.	0.004" (0,1016 mm)
Lateral runout, max. T.I.R.	0.003" (0,0762 mm)
Pilot dia. runout, max. T.I.R.	0.0025" (0,0635 mm)
Shaft runout, max. T.I.R.	0.0025" (0,0635 mm)
Number of sections, max.	1 (not gangable)
Weight, max.	1.5 oz. (42,5 gm)
Moment of inertia	3,0 gm-cm²
Static stop strength, max.	48 oz-in. (0,339 N•m)

Standard Resistance Values Stocked

1,000Ω	10,000Ω
2,000Ω	20,000Ω
5,000Ω	50,000Ω



Special Features

The following standard features are available on special order:

CT — center tap	SS — slotted shaft
LT — linearity tape	SL — shaft lock
FS — flatted shaft	ST — stop

Environmental

Ambient temperature range	−25° to 105°C
Temperature cycling	5 cycles, −25° to 105°C
Shock	100 g's, sawtooth
Vibration	10 - 500 Hz, 10 g's
Humidity	Five 24-hour cycles
Temperature storage	1,000 hours at 105°C
High and low temperature	mechanical operation at −25° and 105°C
Life expectance	2 million shaft revolutions
Resistance stability	4% max. change from total resistance after 1,000 hours at rated power

Ordering Information

Example: 3371 R1K L.50

Model — 3371; Resistance Value — R1K; Linearity — L.50

BECKMAN®

Technical Bulletin

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Min. practical independent linearity	±0.25%*
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Input voltage, max.	400V DC or within power rating
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Insulation resistance	1,000 megΩ
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Electrical continuity travel, min.	350°
Output smoothness, max.	0.1%
End voltage, max.	0.5% of E_{in}
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Number of turns	single-turn
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Starting torque, max.	1.0 oz-in. (0,0071 N•m)
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Shaft radial play, max.	0.004" (0,1016 mm)
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Shaft runout, max. T.I.R.	0.0025" (0,0635 mm)
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Moment of inertia	3.0 $gm\text{-}cm^2$
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Standard Resistance Values Stocked

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5,000Ω	50,000Ω

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CT — center tap	SS — slotted shaft
LT — linearity tape	SL — shaft lock
FS — flatted shaft	ST — stop

Environmental

Ambient temperature range	−25° to 105°C
Temperature cycling	5 cycles, −25° to 105°C
Shock	100 g's, sawtooth
Vibration	10 - 500 Hz, 10 g's
Humidity	Five 24-hour cycles
Temperature storage	1,000 hours at 105°C
High and low temperature	mechanical operation at −25° and 105°C
Life expectance	2 million shaft revolutions
Resistance stability	4% max. change from total resistance after 1,000 hours at rated power

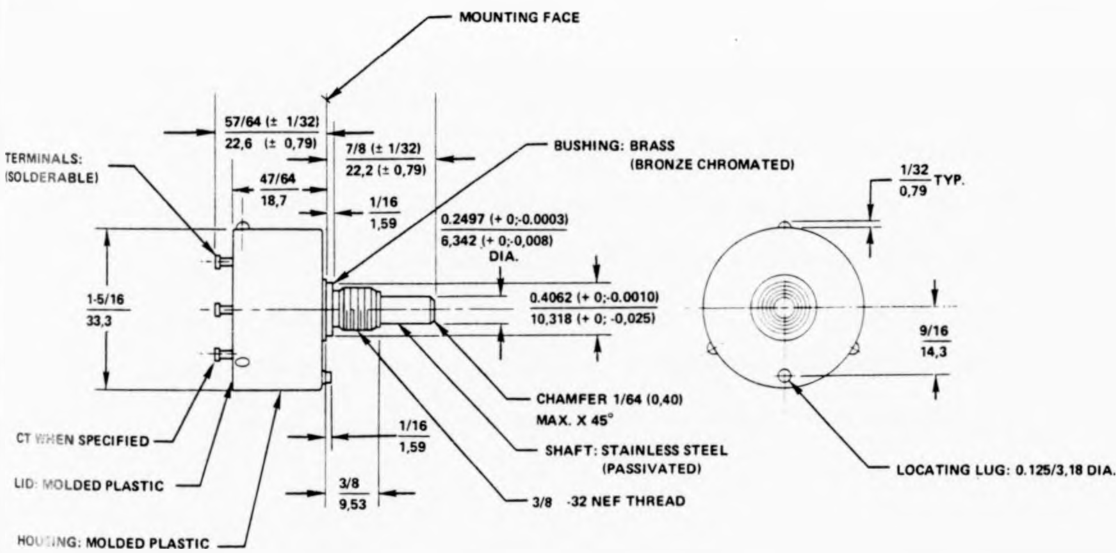
Ordering Information

Example: 3371 R1K L.50

Model — 3371; Resistance Value — R1K; Linearity — L.50

BECKMAN®

MODEL 3371 OUTLINE DRAWING



DIMENSIONS
INCH
(mm)

BECKMAN

Beckman Instruments Limited · Components International · Queensway, Glenrothes · Fife KY7 5PU, Scotland
Telephone: 0592-75 3811 · Telex: 72135 · Cable: Beckman Glenrothes Telex

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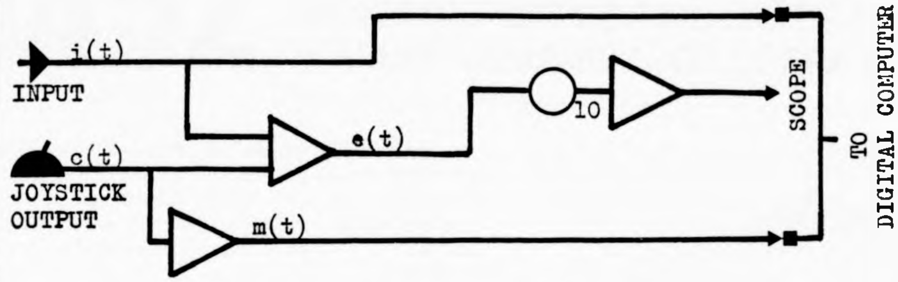
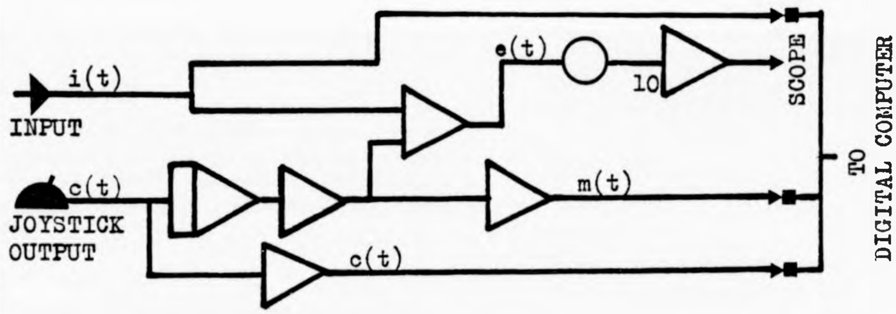
APPENDIX B

COMPUTER FLOW CHARTS OF ZERO, FIRST AND SECOND ORDER CONTROL SYSTEMS

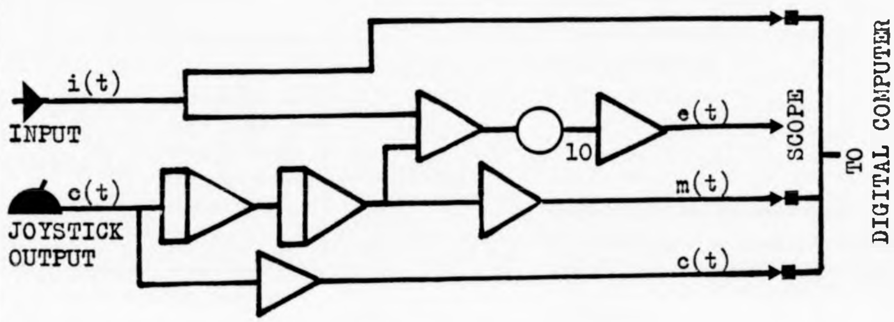
Flow charts of zero, first, and second order control dynamics. Conventional symbols are used to represent analog computer logic. Note that zero first and second order control systems are characterized by the number of successive integrations of the controlled element output c(t). Each order of control diagram represents the analog program implemented for visual tracking. Identical programs (not represented) were implemented in the analog computer to enable auditory tracking with zero first and second order control dynamics. Potentiometer readings and other electronic adjustments, characteristic only of the equipment used in these experiments, are not represented.



ZERO ORDER CONTROL SYSTEM



FIRST ORDER CONTROL SYSTEM



SECOND ORDER CONTROL SYSTEM

TELEDYNE PHILBRICK

4452 GENERAL PURPOSE MULTIPLY-DIVIDE-SQUARE-SQUARE ROOT OPERATOR

The Model 4452 is an economy multiplier/divider that requires only two external components to achieve maximum performance. Its small size and low cost make it an excellent choice for use as a computing element in the laboratory, in manufactured equipment, or wherever a multiplication process is required with no limitations on the polarity of input signals.

Unlike monolithic IC multipliers and most discrete multipliers, the Model 4452 requires no external amplifiers or circuitry, other than the two 50kΩ trimming potentiometers, for performing multiplication, division, squaring, or square-rooting. Selecting the mode of operation is determined by connecting the output of the module to the appropriate input pins.

The Model 4452 is fully encapsulated in epoxy for complete mechanical protection and for an almost completely isothermal environment for superior stability. The unit is short-circuit protected and the inputs are protected against overvoltage.

APPLICATIONS

As a multiplier there are no limitations on the polarity of input signals. Like other multipliers, when the 4452 is connected as a divider, the numerator, Z, can be either polarity, but the denominator, Y, must be positive and of such a magnitude that the output will not be required to exceed 10 volts in magnitude.

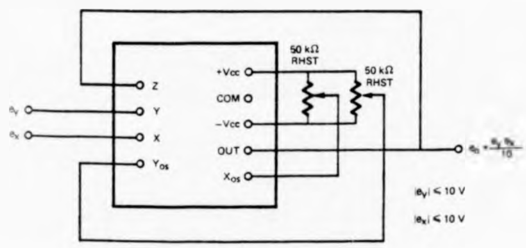


Figure 1A. Multiplication Mode

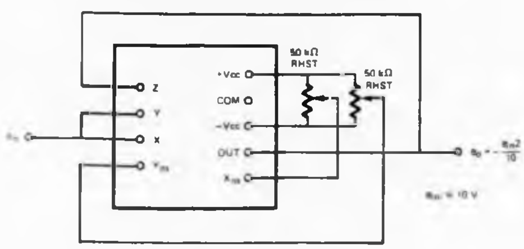


Figure 1B. Squaring Mode

FEATURES

- Low Cost
- Small Size
- High Input Impedance
- 4 Quadrant Operation
- No External Amplifiers Required

APPLICATIONS

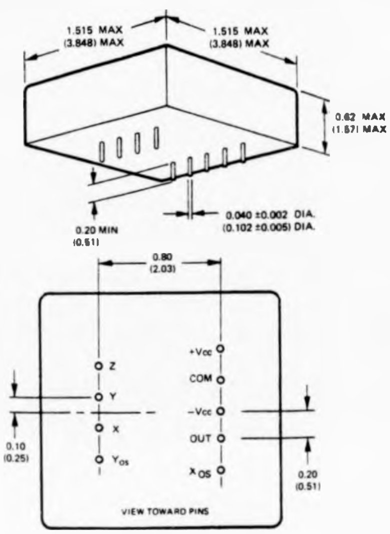
- Automatic Gain Control
- Power Measurements
- Carrier Modulator/Demodulator
- Auto-Correlator
- Phase Detection

Multiplication and Squaring Mode

1. Connect the Z terminal to the OUT terminal.
2. Set X = 0 volts and Y = ±10 volts at 100 Hz. Adjust X_{OS} for minimum output null as displayed on an oscilloscope.
3. Set Y = 0 volts and X = ±10 volts at 100 Hz. Adjust Y_{OS} for minimum output null as displayed on an oscilloscope.
4. For use as a squarer, connect terminal Y to terminal X.
5. For use as a modulator, the carrier should be applied to the X terminal and the modulator to the Y terminal. Carrier null suppression is performed by adjusting the X_{OS} potentiometer for dc offset, and the Y_{OS} potentiometer for symmetry.

SPECIFICATIONS Typical @ 25 °C V_{CC} = ±15 V (unless noted otherwise)

TRANSFER FUNCTION		
Multiply Mode		$V_{out} = \frac{-x \cdot y}{10}$
Divide Mode		$V_{out} = \frac{-10z}{y}$
Accuracy, % of Full Scale Trimmed		
4-Quadrant Operation		2% max.
2-Quadrant Operation		1% max.
INPUT		
Voltage		±10 V
Impedance	X Input	40 kΩ min.
	Y Input	30 kΩ min.
	Z Input	90 kΩ min.
OUTPUT		
Voltage		±10 V
Current		±5 mA
Impedance		1 Ω
FREQUENCY RESPONSE		
−3 dB point		400 kHz
1° phase shift		2 kHz
Full Output		40 kHz
STABILITY		
Output Offset		
vs Temperature		3 mV/°C
Output Noise		2.5 mV RMS
TEMPERATURE RANGE		
Operating		0 °C to +70 °C
Storage		−25 °C to +85 °C
POWER REQUIREMENTS		
Supply Voltage		±15 VDC ±1%
Current, Rated Output		±15 mA
Quiescent		±5 mA



±0.01 Non-cumulative tolerance between pins
±0.02 Tolerance from case edge to center of pin

DIMENSIONS IN PARENTHESES ARE EXPRESSED IN CENTIMETERS

Optional Socket: NSK-20

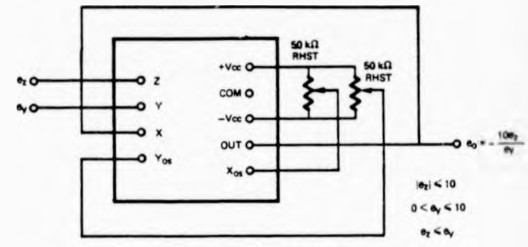


Figure 2. Division Mode

Division Mode

1. Connect the X terminal to the OUT terminal.
2. Set Y = +10 volts and Z = 0 volts. Adjust X_{OS} for a minimum output null as measured on an oscilloscope.
3. Set Y = +10 volts and Z = +10 volts. Adjust Y_{OS} for −10 volts output.

Note: Y must be positive when used as a divider, and of such value as will not require the output to exceed 10 V magnitude.

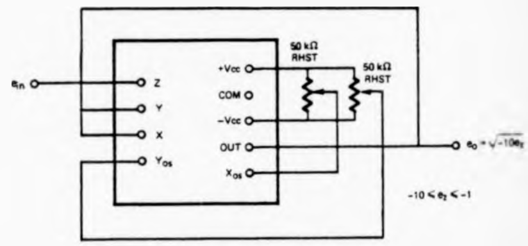


Figure 3. Square Root Mode

Square Root Mode

1. Connect terminals X and Y to the OUT terminal.
2. Set both potentiometers to approximately mid range.
3. Set Z for −10 volts. Adjust the Y_{OS} potentiometer for an output of +10 volts.
4. Set Z for −1 volt. Adjust the X_{OS} potentiometer for an output of +3.16 volts.
5. Repeat steps 3 and 4 until the required outputs have been obtained.
6. Voltage applied to Z should be between −1 volt and −10 volts.

TELEDYNE PHILBRICK

AUDITORY DISPLAY SYSTEM

The auditory display consisted of a pure tone which could be played to the subject over stereo headphones. The amplitude of the tone at each headphone varied inversely so as to keep a constant combined output level.

A random, time-varying, control signal (tracking error) was processed by two operational amplifiers (see circuit diagram below), summed with offset voltages to produce two antiphase outputs as follows:

Control	-10v	0	+10v
Amplifier 1 output	10v	5	0
Amplifier 2 output	0	5	10

As can be seen in the circuit diagram, the amplifier outputs are applied to the Y inputs of each channel signal multiplier. The output of each multiplier is characterized by the following function:

$$\text{OUTPUT} = \frac{X \cdot Y_m}{10}$$

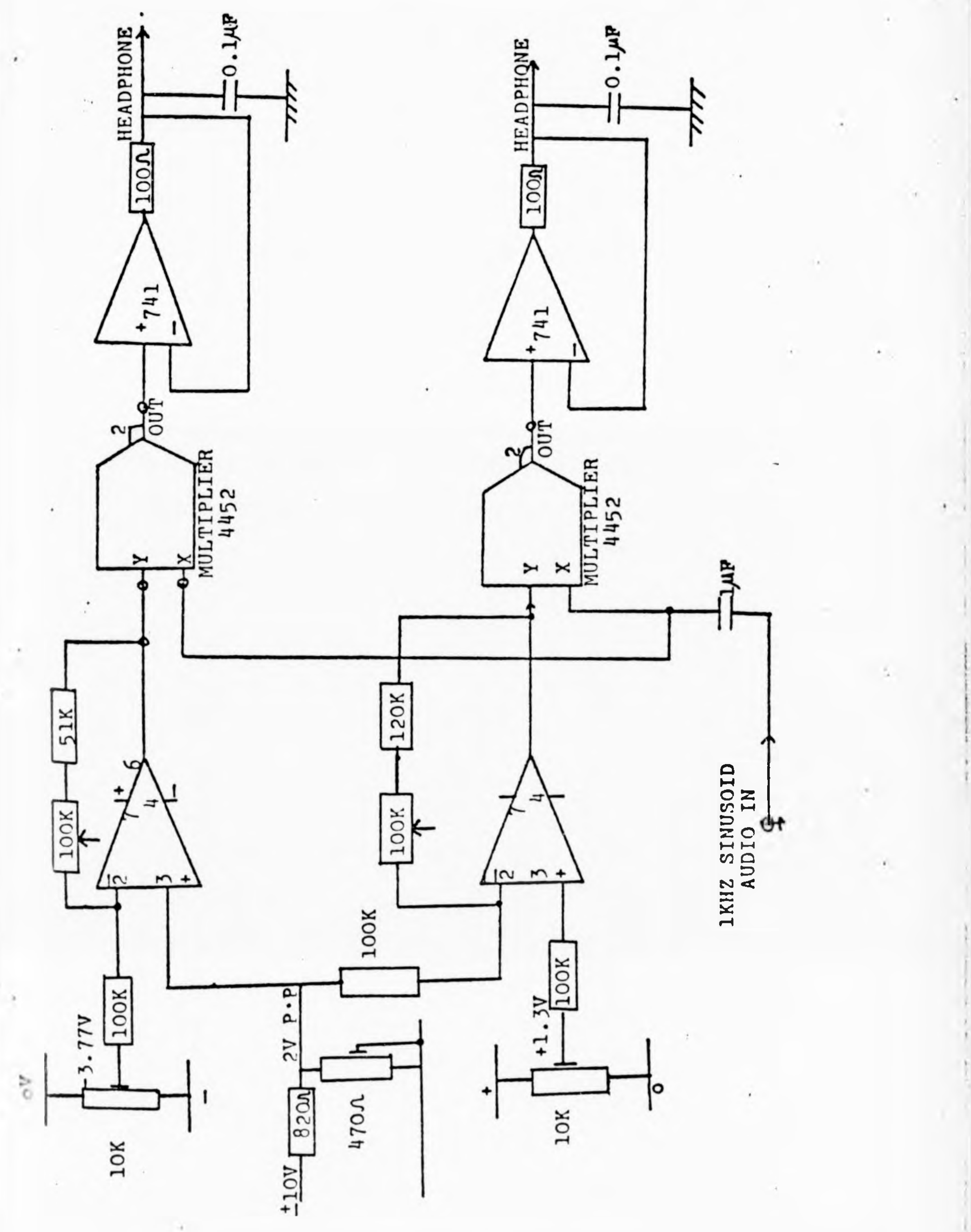
where X = Common audio input (pure sinusoid)

Y_1 = Channel 1 amplitude control

Y_2 = Channel 2 amplitude control.

Hence, for voltage = 0, $Y_1 = Y_2 = 5$; each channel delivering half the total output.

At each limit of the ±10v control signal input range, one of the channels would be full output, and that of the other zero. The channel delivering more output would reflect the sign of the signal voltage.


HEADPHONE
0.1µF
100Ω
741
HEADPHONE
0.1µF
100Ω
741
2
OUT
MULTIPLIER
4452
Y
X
2
OUT
MULTIPLIER
4452
Y
X
1µF
51K
100K
120K
100K
1KHZ SINUSOID
AUDIO IN
100K
100K
100K
0V
3.77V
10K
2V P·P
820Ω
470Ω
±10V
+1.3V
10K

AUDIO DISTORTION	<.5% 100Hz - 10KHz
NOISE ON OUTPUT	<4mVrms
LINEARITY	2%
MAX AUDIO INPUTS	±10V pp
CONTROL INPUT	±10V
FREQUENCY RESPONSE	15Hz - 20kHz
MATCHING BETWEEN STATIONS	±1%

APPENDIX D

The set of instructions in Experiment 1 were essentially the same as those in the other experiments. Except verbal descriptions of the experimental manipulations were tailored to each subject individually.

General Instructions Experiment 1 and others

Thank you for taking part in this experiment. On the table in front of you there are two joysticks labelled VISUAL and AUDITORY respectively. By means of these devices you will be able to control the position of either a line on the screen in front of you, or a tone which will be presented by the headphones. You will note that moving the joysticks from side to side results in movement of either the line or the tone (inside your head from ear to ear). Several times during the experimental session you will be required to 'center' the line in the middle of the red rectangle and the tone in the 'center' of your head. Using the joystick you should practice doing this. You will immediately find that during each trial the line, or tone, will not remain still when you leave the joystick still. Therefore, you must compensate the best you can to keep them centered at all times. This will be easy to do after a little while.

During the experimental session there will be several trials or runs. These will last for a little over a minute.

Each one will begin with a displacement of the tone,or line,and a continuous disturbance. This disturbance will interfere with your centering of the line or tone. By means of the joystick(s) you should strive to keep the line, tone,or both,centered at all times. Any movement of the line or tone reflects your inability to control the position of the display. Therefore, this movement reflects your error. You must keep this error to a minimum by making the appropriate corrections using the corresponding joystick(s). At the end of each run the disturbance will disappear and only the joystick activity will be present. We will now do a few minutes practice to get you acquainted with the process of centering. OK?

At the end of each run it is very important that you center the tone or line, or both, depending on the displacement that occured. This will enable me to make any adjustments in the equipment. Every so often,there will be a rest period that will last approximately 4 minutes. During this period you will also be given feedback about your performance.

Be sure that you do your best at all times to reduce the amount of line or tone displacement. Is everything clear? If you have any questions, now is the time to ask them.

Let us begin.

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