DISPLAY-CONTROL INTEGRALITY AND HETEROGENEOUS DYNAMICS IN DUAL-AXIS TRACKING

by

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DISPLAY - CONTROL INTEGRALITY

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DUAL-AXIS TRACKING.

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Abstract

Several explanations are possible for the performance decrements which occur when tasks are performed concurrently. Capacity theories describe the ability of parallel processing up to a certain point at which a processing "bottleneck" occurs and serial processing becomes necessary in order to prevent further decrements. The stage of processing at which the bottleneck occurs has come under considerable debate. Ample evidence has been cited for either perceptual (early) bottlenecks or response (late) bottlenecks depending on the task combinations studied. More recent research has been successful at describing the "bottleneck" limitations as a resource effect suggesting that performance decrements occur when there is competition between tasks for scarce resources. An opposing view to multiple resource theories suggest that performance decrements are a direct result of cross-talk produced by processing throughputs and outputs between the two tasks.

A manual tracking paradigm was designed in an attempt to determine the effects of display-control integrality and control-order when two heterogeneous controlled element dynamics are combined in dual-axis tracking. This paradigm was used in an attempt to determine the effectiveness of existing theories of divided attention at predicting and describing performance decrements when dissimilar tasks are performed concurrently. Twenty-eight male and four female subjects (N = 32) were randomly assigned between two integrality (integrated, separated) display-control configurations, and two control-order (low,high) conditions. Also, three emphasis conditions were studied: equal-emphasis (effort) on each axis, and two conditions of 25% effort on one axis, 75% effort on the other. Data were collected and analyzed for single and dual-axis tracking trials. Root mean square error (RMSE), control speed, response hold, and control-theory parameters were analyzed in an attempt to identify the source and magnitude of performance decrements under these conditions.

Results indicated that better RMSE performance was achieved for the position, velocity, and acceleration controlled element dynamics when the integrated configuration was used (p=.050, p=.012, p=.034), and these results were replicated for the RMSE decrement scores (p=.035, p=.016, p<.001). However, there was evidence for a resource advantage for the separated conditions as evidenced by control speed for acceleration tracking (p=.021), and by integrality x control-order interactions for gain intercept (p=.016), response hold (p=.020), and control speed (p=.051) with velocity tracking. Integrality x control-order interactions for gain slope and phase intercept indicated cross-talk was most evident when integrated displays and controls are present with high-order controlled element dynamics. Mental workload data indicated that subjects perceived a higher workload in the separated conditions (p<.05), an indication of greater resource expenditure. Separated configurations imposed the cost of visual scanning between the two display cursors. This cost was most evident when low-order (easy) control dynamics were present since the additional response-related resources afforded by two-handed control were not required for effective control. Although, the parameters measured here indicated a resource and cross-talk advantage for the high-order separated condition, they were insensitive to the breakdown of the two-handed channel and could not effectively describe RMSE data. The present data suggest that both resource limitations and confusions account for the performance decrements associated with dual-axis tracking.

Dedication

to my wife, Laurie,

and my parents, Debbie & Marvin

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I would like to extend my sincere thanks to the following people who aided in the formation and completion of this study.

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Preface

The role of attention is central to the characterization of the human as an information processing system. Speculation about the structure and capacity of attentional constructs has provided many plausible theories of human performance. However, a widely accepted, unified descriptor of attention does not yet exist. Therefore, it is not possible to provide a clear explanation for the vast body of results accumulated throughout the literature. Nor, are we able to accurately predict human performance in modern, complex systems. To address these concerns, I feel it is necessary to combine many facets of the existing knowledge into a more tolerable state of organization. I do not predict immediate success in this journey, but rather, I foresee a clearer understanding which will steer a course toward appropriate future directions.

I. Introduction

This introduction provides a brief overview of the research which has led to the formation of this thesis. Greater detail is provided in the review of literature section.

Limitations appear in human performance when multiple demands must be met. Decreasing the volume of the car-radio when parallel parking is probably one of the sillier examples of this. More severe instances of human error due to multiple demands on attention have been documented, particularly in aviation, and need not be repeated here. Usually, these incidents are reported as "pilot-error" initially, but are often re-classified as "human-factors problems" later. Extensive research in the areas of psychology, human factors, engineering, and related areas have made significant strides toward understanding the capacity of the human operator in multiple-task environments, and have aided in the design of ergonomic man-machine systems. This research attempts to describe the current understanding of divided attention and to further the development of this understanding by examining human performance in a complex manual control system.

When two tasks are performed concurrently the performance of at least one of the tasks will usually be poorer than when it is performed in isolation. Humans have a limited capacity to process information relevant to the successful completion of any task. Performance will decline when a single task or combinations of tasks exceed the available capacity (Broadbent, 1958). Dual-task performance decrements are also said to occur because of the demand imposed by timesharing two tasks. The capacity or *resources* demanded by a "high-level executive" in order to delegate attention between two tasks serves to further limit the available capacity (Moray, 1967).

There have been instances where performance decrements did not occur in a dual-task paradigm. That is, perfect timesharing was demonstrated. Wickens (1976) demonstrated this effect with tracking and signal detection, and Allport et. al. (1972) illustrated perfect timesharing when sight-reading music and auditory shadowing tasks were combined. Multiple resource models of attention are best able to describe effects such as perfect timesharing. In contrast to a fixed capacity of resources for all tasks, or a resource-demanding higher-level executive model, multiple resource models posit separate, differentiated pools of resources. When tasks draw from completely non-overlapping resources then perfect timesharing can occur. Wickens (1980, 1984) has suggested that modalities of input and output, information processing codes, and the stage of processing, might define separate resource pools. Friedman et. al. (1981) have developed a model of separate resources which differentiates resource pools by cerebral specialization. Since each hemisphere defines a separate resource this model is easily testable (and disprovable) by varying the isolation of each hemisphere in a dual-task paradigm. Considerable evidence for the independent hemisphere model has been provided by Friedman and her colleagues (Friedman et. al., 1981,1982,1988; Herdman & Friedman, 1985).

The context in which tasks are completed also affects dual-task performance. For example, if two identical tracking tasks are combined then the proximity of the displays and controls should be compatible with the tasks in order to optimize performance. Compatibility of proximity hypothesis (Kramer et. al, 1985) suggests that if two tasks require the same information processing strategies (i.e., tracking in two axes with identical control dynamics on each axis) then it is beneficial to combine the displays for each axis into a single, integrated cursor. Similarly, integrating the controls for each axis into a single, integrated control will further improve the proximity between processing stages. Compatibility of proximity simply refers to the similarity of the level of proximity at each processing stage. As the compatibility of proximity increases, performance is expected to improve.

The notion of proximity of processing stages is analogous to stimulus-response mapping models. For example, Duncan (1979) showed that performance declined as S-R mappings became less compatible. When tasks are combined the processing of one has the potential to affect the other. Similar or identical tasks are often said to interfere with each other and cause performance decrements because they require the same resources. However, dissimilar tasks are also subject to dual-task decrements. Kelso et. al. (1979) noted contamination in the timing patterns of ballistic hand movements when temporally incompatible movements were performed concurrently. Chernikoff et. al. (1963) and Fracker & Wickens (1989) have noted performance decrements when tracking tasks with different control dynamics were combined. In these situations, the performance of the least-difficult task is usually corrupted by the more-difficult task. This interference, or cross-talk, between the processing of tasks performed concurrently is useful for explaining dual-task performance decrements, and is preferred by theorists who argue against the notion of multiple resources (Hirst & Kalmar, 1987; Navon, 1984; Navon & Miller, 1987).

Multiple resource theory, confusion theory, and compatibility of proximity hypothesis can be quite complementary when predicting performance for certain task combinations. Fracker & Wickens (1989) used a dual-axis tracking paradigm to illustrate this point. These authors manipulated the heterogeneity of the control dynamics of the tracking axes, and also the display and control configurations. Velocity or acceleration control dynamics were either combined on both axes (homogeneous), or combined together with one dynamic on each axis (heterogeneous). Displays and controls were either integrated or separated. Resource theory was supported when root mean square error for the acceleration axis was found to be larger when the dynamics were homogeneous (acceleration/acceleration) than when they were heterogeneous (velocity/acceleration). Since tracking with acceleration control dynamics is said to be more resource demanding than velocity tracking, the combined demand of acceleration/acceleration is greater than the heterogeneous (velocity/acceleration) condition. One might have expected more confusions to occur between the tasks that required different response strategies. However, confusions were evident when velocity tracking was combined with acceleration tracking. The slopes of the gain functions for the human operator performing velocity tracking steepened toward the slopes measured for the acceleration axis. This finding seemed to indicate that the control of the velocity axis was contaminated by the control of the acceleration axis. Finally, compatibility of proximity hypothesis was supported in their research. Superior performance was demonstrated when homogeneous control dynamics were paired with integrated displays and integrated controls.

Although, Fracker & Wickens (1989) provided a thorough account for dual-axis tracking performance with homogeneous control dynamics, their results were inconclusive when control dynamics were heterogeneous. For example, it was unclear whether performance was better when displays and controls were integrated or separated. The present study was designed in order to determine the effect of display-control integrality for a tracking system with heterogeneous dynamics.

II. Review of Literature

A. Theories on the Limitations of Human Performance

Several explanations have been offered for the limitations of attention. A very brief discussion of early theories of attention begins with the notion of a limited capacity central processor, and is followed by a more well-defined structural account for human performance limitations. A more thorough examination of capacity theories and the energy or *resource* metaphor is then offered. Finally, multiple-resource models of attention are examined and theories opposing the resource framework are discussed.

i) The Limited-Capacity Central Processor (LCCP)

William James (1890) discussed the limitations and regulation of consciousness in the following manner:..

> Every one knows what attention is. It is the taking possession by the mind, in a clear and vivid form of one out of what seem several simultaneously possible objects or trains of thought...
>
> ...The number of things we may attend to is altogether indefinite, depending on the power of the individual intellect, on the form of the apprehension, and on what the things are. When apprehended conceptually as a connected system, their number may be large. But however numerous the things, they can only be known in a single pulse of consciousness for which they form one complex "object", so that properly speaking there is before the mind at no time a plurality of IDEAS, properly so called.

This notion was strict in describing events as "single" entities and that any single event could encompass the consciousness entirely. This is structurally analogous to the concept of a LCCP where James tended to identify the limitations of attention (the central processor) as competition for the possession of consciousness.

In later years, the LCCP concept was more formally developed in part by Shannon & Weaver (1949) who proposed the concept of the communication channel which exists between any two points. Shannon-Weaver information-theory, as it became known, speculated that communication channels vary in capacity and that channel capacity can be quantified within an information theory framework. Full-capacity channels display no information degradation from sender to receiver, whereas partial-capacity channels are corrupted by noise along the channel.

Channel capacity became a useful measure of central processor limitations. For example, Garner (1962) provided a summary of studies which modelled the human as a communication channel with a capacity to transmit information based on the sensory modalities used to make unidimensional absolute judgments. Channel capacity was as high as 3 bits of information transferred for the visual channel and as low as 2 bits of information for taste. Hick (1952) and Hyman (1953) were important pioneers of information theory-based quantification of human performance in the motor control domain. The Hick-Hyman Law expanded upon the channel capacity metaphor for describing choice reaction time (CRT) also as a function of information in bits. Miller (1956) was able to quantify short-term memory capability using the channel capacity framework. Miller's "magical-number 7 plus or minus 2" was the equivalent of about 2.5 bits of information. The concept of the "chunk", the composite unit resulting from the grouping, organizing, or recoding of seemingly isolated elements, served to steer the basis for channel capacity computations away from particular list elements. This served to detract from classical information theory in that information rate could no longer be expressed as a physical property of stimuli or the task itself. Similarly, the Hick-Hyman Law, although useful in predicting human performance within a speed-accuracy framework, was unable to describe CRT differences as a function of stimulus-response compatibility or level of practice.

ii) The Single-Channel Bottleneck

Information theory provided a quantifiable limit of about 2.5 -3 bits per second on the information processing system. From the studies cited above it also became clear that different tasks impose different demands which load the human processor to different extents. Because certain tasks might consume only a portion of the capacity (say 1.5 bits/sec), the notion of spare capacity was postulated (perhaps 1-1.5 bits of residual capacity).

Broadbent (1958) proposed a model of attention which described the flow of information. Broadbent retained the idea of the limited capacity channel, but preceded it by a selective filter and short-term sensory store. In this model the central processor operates on the long-term sensory store and the response mechanisms. The filter allows the flow of information to the processor based on physical features of the input and communication with the long-term sensory store. This prevents the unwanted processing of irrelevant stimuli which is costly to performance. Broadbent's model predicts that performance bottlenecks occur at early stages of processing (at the filtering stage). For example, in the work of Treisman & Gelade (1980) it was demonstrated that tasks which require the integration of separate physical attributes in a stimulus array imposed a greater workload on subjects.

Like Broadbent, Welford (1967) offered another single-channel bottleneck model, but his model identified the central processor as the limiting source within the system. Welford designed temporally-based paradigms to demonstrate that a psychological refractory period (PRP) exists between responses to closely spaced stimuli. This performance-limiting delay, Welford argued, was due to a single-channel decision mechanism which is occupied by feedback from movement execution and termination, and is increased as the inter-stimulus interval (ISI) is decreased. These findings were enhanced by the work of Keele (1973) who also argued a late-selection theory which localized serial processing bottlenecks at the response selection stage, preceding either overt or covert responses.

Controversy between early and late-selection models served to diminish single-channel theories. Evidence against Broadbent's early-selection model was provided by the work of Treisman (1960, 1965) who did not show proportional shadowing performance in a dichotic-listening paradigm as a function of information content. Broadbent's assumptions that information presented to the irrelevant ear would not reach the level of semantic analysis were not upheld. Kahneman (1973) argued the validity of the late-selection model by examining the inter-response interval (IRI) in place of the ISI studied by Welford. The IRI analyses provided evidence for the parallel processing of two stimuli i.e., processing of the second stimulus begins before the completion of the response to the initial stimulus. Another filter model was proposed by Treisman (1964) which served to refine the original work of Broadbent. The filter was assumed to attenuate rather than completely block information in the unattended channel (to accommodate the known effect of shadowing in dichotic listening tasks), and could operate along the entire information processing path (rather than at the perceptual stage only). Treisman's filter was described as a "selective attention strategy" (Treisman, 1969) rather than as a fixed structure, and four types of attention strategy were offered. These included the restriction of input stimuli and the dimensions analyzed, the sets of critical features which are monitored, and the decision for behavior and memory base on perceptual analysis. However, as noted by Gopher and Donchin (1986), this variant of a single-channel model took great liberties with the "channel concept "...

> "In fact, the very notion of a channel loses much of its value when it refers to an ensemble of processing entities that communicate with each other under complex control schemes"

It is in fact, the structural complexity of the human information processing system that has turned researchers away from the LCCP and structural theories. Modern analyses of the information processing system became costly and confounded by complex architecture. It was for this reason that during the early human factors studies of the measurement of human-operator workload, Knowles (1963) proposed a conceptual model of the human operator possessing a pool of limited capacity resources. He postulated that these resource pools could be allocated and divided in graded quantities among separate activities. This work and the work of others (eg., Moray, 1967) enticed psychologists to examine the capacity of the human information processing system in a new light.

iii) Capacity Theories and Single Resource Theory

Moray (1967) argued that the localization of early or late processing bottlenecks was unfounded. He proposed a higher-level system analogous to a computer to describe the human information processing system. In this model, each of the stages of processing is overseen by a higher-level executive "program" which is responsible for the allocation of resources to any activity or processing stage which requires them. Interference would depend upon capacity demands at any stage of processing and performance limitations would result if such demands could not be met. Taylor, Lindsay & Forbes (1967) described a quantitative *capacity-sharing* theory between perceptual input channels thereby providing an alternative from previous "all-or-none" accounts of attention.

Kahneman (1973) shared this capacity-limitation view and proposed an energetic model of capacity. The available capacity in the system is determined by the level of arousal which varied according to the well-known inverted-U function relating performance to arousal. This capacity is shared among activities based on an allocation policy which integrates activity demands, momentary intentions, and feedback from activity execution.

Wickens (1984) borrowed equally from Kahneman (1973), Norman & Bobrow (1975) and Navon & Gopher (1979) in describing three basic elements which are at the foundation of resource theory. These he states, are the performance-resource function, the performance operating characteristic, and automation and task difficulty. The work of Norman & Bobrow (1975) served to identify to two types of performance: data-limited performance, and resource-limited performance. Figure 1a illustrates a hypothetical performance-resource function (PRF) which describes performance quality plotted against the amount of resources invested. A task is said to be resource-limited when an increase in effort, resources, etc. increases the level of performance. The task is data-limited when additional resource investment does not yield a subsequent performance increase. For example, a very simple task (reaction time), is data-limited because a subject can reach a performance ceiling and still have enough residual capacity to perform simple mental arithmetic calculations.

Navon & Gopher (1979) used a macro-economic metaphor to compare human dual or multiple-task performance with that of a manufacturer of many products who has to optimize the allocation of resources such as labour, money, equipment, etc. They described dual-task performance through the use of performance operating characteristics (POC), two of which are illustrated in Figure 1b. The performance of two tasks can be determined from the performance-resource functions with different resource allocation policies and thus the performance of both tasks can be plotted against each to form the POC. Single-task performances are plotted on the respective axes while dual-task performances at several allocation combinations are plotted within the POC. Several POC shapes are possible and Wickens (1984) describes five points of interest.

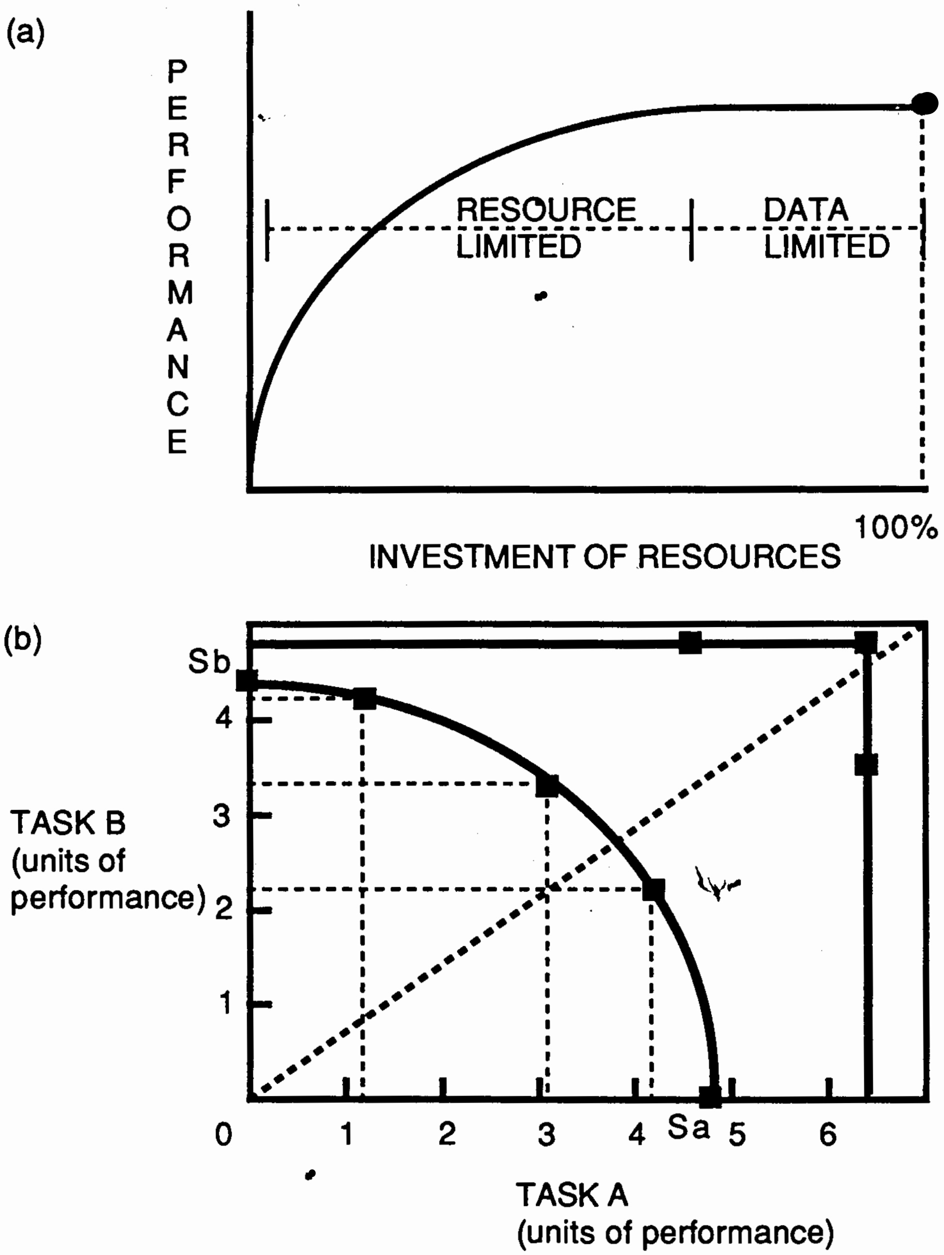


Figure 1- a) Performance-Resource Function. The relationship between resource investment and peformance. Performance can be limited by resources or data. b) Performance Operating Charateristics. The curved POC illustrates tasks which trade-off performance under different resource allocation policies. Single task performance is denoted on the respective axes. A box-like POC is found when tasks do not share common resources.

The first is that of *single task performance* which has already been discussed. It is of interest to note that if two tasks are performed but the subject is instructed to fully attend to only one task, and the performance on that task does not reach the level of single-task performance given in the POC, then a *cost of concurrence* is said to exist (Navon & Gopher, 1979). This concept is analogous to the higher-level resource allocation system proposed by Moray (1967), where the executive which allocates resources to various activities also consumes resources for its duties. Nothing in this world is free. The second feature Wickens describes in the POC is *time-sharing efficiency*. The closer the POC falls to the single-task performance region, the more efficient the time-sharing. The *degree of linear exchange* indicates the extent to which resources removed from one task can be utilized by the other. This follows the work of Norman & Bobrow (1975) in that if a task is data-limited then the removal of resources from it will not detract from the performance, or similarly, the addition of resources to a data-limited task will not further benefit performance. However, the removal of resources can reduce performance in a resource-limited task. And so on. A box-like or discontinuous POC indicates that either of the two are in a data-limited region, or that resources are not interchangeable between the two tasks. *Allocation bias* describes the disposition of the POC to fall away from the diagonal toward a certain axis. This indicates a shift in resource allocation toward that axis. Finally, *efficiency and allocation in combination* are addressed in the POC space. Two problems are encountered when comparing differences between points in the POC space that differ in efficiency and allocation and do not lie along the positive diagonal. First, performance measures on the two tasks may be expressed in different units, and second, a unit change in performance cannot readily be mapped to a unit change in resource allocation. The former problem can be alleviated by normalizing the POC space, the latter by knowing the form of the PRF for each task.

Task difficulty and automaticity also have important implications in resource theory. Tasks of varying difficulty or level of performance will exhibit different PRFs. Tasks that do not reach a data-limited asymptote are assumed to be more difficult or less automated than tasks that do. Also, when combined with another task, a difficult (resource-limited) and easy (data-limited) task can reach an equivalent level of performance, but there is a residual capacity left-over from the easy data-limited task that does not exist with the resource-limited task. Further, two data-limited tasks can differ with respect to their data-limited asymptotes but not in their level of performance. The higher the asymptote the more automated or less difficult the task becomes, i.e., the smaller the data-limited region.

Resource theory has an intuitive appeal for describing performance decrements in the absence of obvious structural deficits. However, further research in the area introduced a number of limitations with a single-resource model. For example, perfect time-sharing was demonstrated by Allport *et. al.* (1972) when subjects were shown to be able to sight-read music and complete an auditory shadowing task without a decrease from their single-task performance. A similar effect was described by Wickens (1976) when a force-generation and signal-detection task were combined. North (1977) identified significant differences in the difficulty of two discrete digit-processing tasks and showed that the more difficult of the two tasks did not disrupt a tracking task to any greater extent than that caused by the easy task. Neither of these studies involved repetitive or predictable solutions, thus neither automaticity nor data-limited explanations seem to provide explanatory power for these occurrences. Further, there have been several investigations which have manipulated the processing structure of tasks in the absence of difficulty manipulations and noted differential performance decrements. For example, Wickens et. al. (1983) have identified these structural alteration effects with display (input) modality, response (output) modality, and central processing codes (eg., spatial versus verbal). The assumption of an undifferentiated pool of resources does not predict a difference in the amount of interference imposed upon a task if the resource demand remains constant across such manipulations.

iv) Multiple Resource Theory

Multiple resource theories have developed from the original capacity and single-resource theories. These theories hold that when tasks are performed concurrently performance will deteriorate if there is competition for the same scarce resources (e.g., Kahneman, 1973; Navon & Gopher, 1979, Norman & Bobrow, 1975; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977; Wickens, 1980, 1984).

The most extensively argued multiple resource model is that proposed by Wickens (1980,1984). The model considers stage of processing (encoding, central processing, response), modalities of input (auditory, visual) and response (vocal, manual) , and processing codes (verbal, spatial) as dimensions of resources. Wickens' multiple resource model is illustrated in Figure 2. Wickens and his colleagues set out to test this theory by devising two experimental techniques designed to identify changes in the POC with resource overlap and with task difficulty manipulations. In order to provide support for their model they attempted to show that a smooth, continuous POC is generated when resources between two tasks overlap, and also that a discontinuous box-like POC is the result of non-overlapping resources. Kahneman's single-resource model is not able to predict perfect timesharing between two-tasks because all tasks must be governed to some extent by the single resource and that some interference must exist unless the tasks are severely data-limited. Vidulich and Wickens (1981) demonstrated nearly perfect timesharing when combining an auditory Sternberg memory-search task with tracking. They also demonstrated a larger spread in the points determining the POC when a visual Sternberg task was shared with tracking as opposed to the auditory task. That is, there was greater resource overlap between the two tasks which required visual resources and thus, there was a greater degree of exchange between the two tasks under priority manipulations. Further, the experimenters were able to demonstrate a task difficulty by priority interaction. Tracking was more disrupted with a second-order control than with a first-order control when manual responses were used for the Sternberg task. This finding followed the premise of Navon & Gopher (1979) that priorities exert a greater influence on performance when the demand for a common resource is high (more difficult) than when it is low. Numerous other experiments by Wickens and his colleagues have demonstrated performance decrements when tasks are shared within common resources, whereas decrements are absent or reduced when tasks are spread between different resources (e.g., Wickens et. al., 1983).

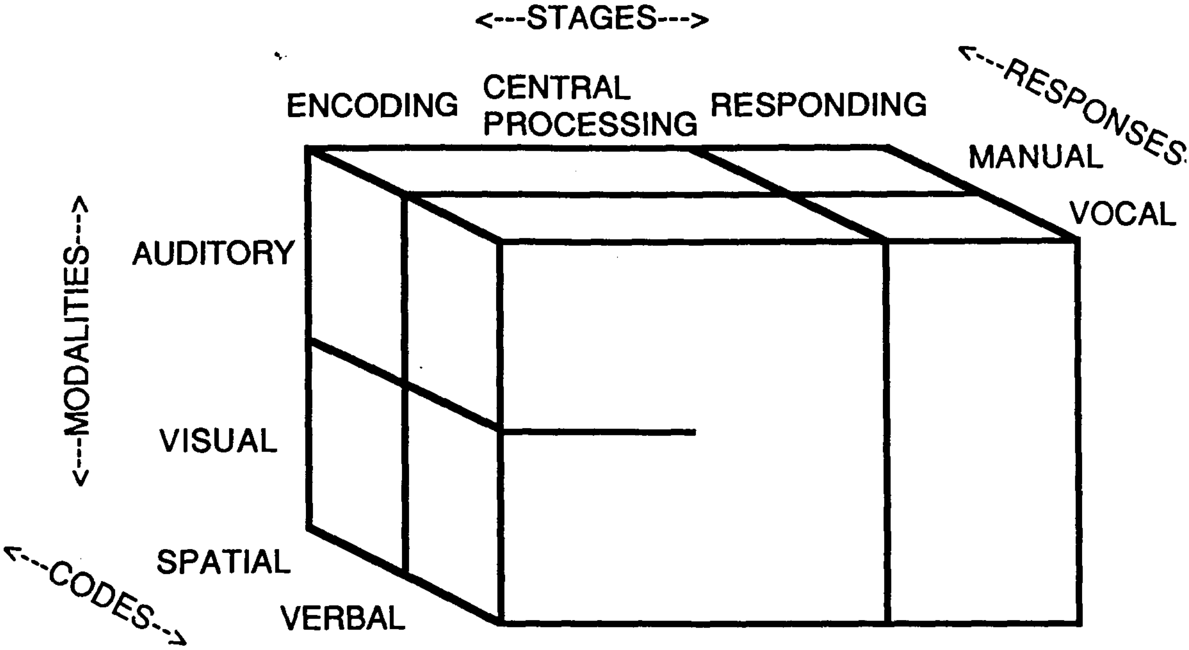


Figure 2- Wickens' Multiple Resource Model (Wickens, 1984). Separate resource pools are proposed for I/O modality, Stage of Processing, and Processing Code. The cost imposed by visual scanning may be resposible for results suggesting input modalities define separate resources.

Friedman et. al. (1981, 1982, 1985, 1988) have developed a multiple resource model which has gained considerable acceptance in recent years. The authors maintain that each cerebral hemisphere accesses an independent resource supply that can be shared among many types of tasks. It is suggested that each hemisphere can encode, centrally process, and respond to verbal and non-verbal information received through either the eyes or ears. This view suggests that processing modality and processing code may be irrelevant in determining the competition for resources, and thus, dual-task performance. The model proposes a greater influence based on the segregation of the two hemispheres and laterality effects. Since each hemisphere can be isolated with respect to vision, audition, and control, the existence of separate resources is more easily tested. Further the theory lends itself more easily to be disproved since it is readily testable.

Friedman *et al.* have consistently stressed the importance of using a task emphasis manipulation to enable interpretation of interference effects. Task emphasis manipulation, as described in the PRF and POC discussions above, allows subjects to weight the importance of each task differentially in the dual-task paradigm. Subjects are provided with a performance/pay-off scheme which favors the emphasis condition imposed. Performance should only trade-off with task emphasis manipulation when there is partial or complete overlap between resources (hemispheric demands). Performance trade-offs with task emphasis manipulation should not exist when two tasks are perceived, processed, and controlled by separate resources, since distinct resources are required for each task. These effects have been demonstrated for intra-modality and cross-modal experiments which served to isolate the demands imposed upon each hemisphere (Herdman & Friedman, 1985).

More recently, Wickens & Liu (1988) provided further evidence for the existence of separate resources between verbal and spatial processing codes. They also re-analyzed the existing data from perceptual modality studies and attributed previous cross-modal (A-V) timesharing advantages to the visual scanning cost imposed on the intra-modal (V-V) condition rather than to a non-overlapping of resources. When the visual scanning cost was removed from the data, there was no difference between cross-modal and intra-modal performance. This re-analysis parallels the previously stated criticisms of multiple resource theory i.e., what constitutes a resource pool, and the number of resources in existence (e.g., Navon, 1984; Navon & Gopher, 1979).

Experimental findings exist that may link these hypothetical commodities known as resources to physically identifiable variables. For example Beatty (1982) provided a comprehensive summary of his work and the work of others (Kahneman et. al., 1969) linking pupillary response and processing effort. As task difficulty increased, pupil dilation was shown to be larger. Although there is evidence linking performance to bloodflow to the brain (Gur & Reivich, 1980), and the metabolism of glucoproteins by the brain (Sokoloff, 1977), it does not seem that these measures would be sensitive within the bandwidth of performance change under resource mobilization (Wickens 1979, 1984). Finally, Kinsbourne & Hicks (1978) conception of functional cerebral space links the proximity of cerebral control centres with dual-task interference effects. That is, the closer the distance between centres, the greater the neuronal interconnectedness, and therefore, the greater the interference due to cross-talk when both centers are orthogonally active. This model does not identify a higher-level executive, but rather presents a lower-level representation of the processing system for the existence of separate resources.

v) Opponents of Multiple Resource Theory

Confusion theory has been developed by theorists who have argued against resource theory for several important reasons (see Hirst & Kalmar, 1987; Navon, 1985; Navon & Miller, 1987 for review). Navon (1985) has argued that tasks could interfere not only because they compete for the same resources but also because each produces outputs or side effects that are harmful to the processing of the other. Cross-talk develops between the two processing channels as the demands of one task become confused with those of the other. Labelled as outcome conflicts, it is suggested that performance is degraded when tasks are processed in parallel, or that serial processing becomes essential in order to avoid such conflicts. Navon & Miller (1987) cite findings such as the Stroop effect (e.g., Logan, 1980) as consistent with the notion of outcome conflicts. That is, cross-talk results between the processes governing the identification of a colour word, and the name of an ink colour. Klein (1964) viewed Stroop-type effects to be dependent on the semantic correspondence between the unwanted and actual responses.

Concern has been raised about the role of confusions in human performance and whether or not confusions increase with task similarity (Navon & Miller, 1987), or whether confusions occur when concurrent tasks require the individual to perform incompatible mental operations (e.g., Duncan, 1979; Kelso et. al, 1979; Klapp, 1979, 1981). Resource theorists are able to explain performance decrements when tasks are similar i.e., require the same resources. Fracker & Wickens (1989) have expressed the need to document the occurrence of confusions across a wide variety of dual-task combinations in order to construct a model of how and when they arise. These authors have also provided evidence that both resources and confusions are needed to explain data from dual-axis tracking results. Their results indicated that resource theory is needed to explain results which showed that tracking error increased when the combined demand imposed by the dynamics on the two tracking axes increased. That is, tracking error was greater when acceleration dynamics were used on both axes than when velocity and acceleration dynamics were combined in a heterogeneous dynamic condition. Because it is more difficult to control with acceleration dynamics, resource theory predicts that a greater demand is imposed in the acceleration-acceleration condition than the velocity-acceleration condition. Confusion theory would predict that there should be no confusions between the control of the two axes in the homogeneous condition whereas confusions between the two axes with heterogeneous dynamics may result. Therefore, poorer performance is predicted in the heterogeneous condition.

Although resource theory seemed better able to account for their results on tracking error, Fracker & Wickens (1989) noted evidence for confusions in the gain slopes of the human transfer functions when tracking with velocity controlled element dynamics. Gain and phase slopes and intercepts provided informative data for their study along with traditional RMSE measures. The gain slope of the velocity tracking axis steepened toward that of the acceleration tracking axis when combined in a heterogeneous condition. This would indicate that tracking the acceleration axis corrupted the subjects tracking on the velocity axis i.e., caused confusions. Also, cross-talk was evident between tracking axes with an integrated control (one joystick, two axes of rotation), and also between separated controls (two joysticks, one axis of rotation each) when an integrated display was used. Their findings will be discussed further in this section.

B. Manual Control and Tracking

Manual control and tracking studies have enabled researchers from a variety of disciplines to speculate on the structure and capacity of the human information processing system. Throughout the 1960s, human performance in manual tracking was studied extensively in order to develop human-pilot models for application in the design of advanced aircraft. The work of McRuer and his colleagues (eg., McRuer & Graham, 1963; McRuer, Graham, Krendel & Weisener, 1965; McRuer & Jex, 1967) extensively documented the capabilities of the human operator in compensatory manual control systems. The earlier studies of simple control systems proposed a simple man-machine model from servo-control theory which became known as the McRuer Crossover Model.

The Crossover Model developed by McRuer and his colleagues uses control theory parameters to describe the human and man-machine system in the compensatory tracking environment. This quasi-linear model describes the linear portion of the human operator (output which is linearly correlated with the disturbance signal) with two parameters, and includes the non-linear portions of the output (that which bears no direct relation to the driving signal) into a single component commonly referred to as remnant. The two parameters which describe the linear-portion of the system are the crossover frequency (ω_c), and the effective time delay (τ_e). The parameter ω_c is directly related to the gain of the system considered, and τ_e is extracted from the phase characteristics of the system. Gain can be defined simply as a proportionality constant that determines how rapidly the output is adjusted relative to the magnitude of the input (or error) i.e., gain is a measure of sensitivity. That frequency where the gain of the system is zero (dB) is denoted as ω_c. Phase is defined simply as the angle in degrees (time) by which the output lags the input. Therefore, τ_e (in seconds) is the slope of phase (in degrees) plotted against frequency (cycles/second), and is largely dominated by neuromuscular and cognitive transmission delays (Jagacinski, 1977). Pew & Rupp (1971) discussed the importance of τ_e and described it as a balance between intrinsic processing delays and anticipatory behavior to predictive trends in the input signal. Therefore, the use of τ_e as a descriptor of reaction time is not prudent when the subject is able to anticipate the input signal, although it has proven useful as a measure which is analogous to reaction time for systems with random or pseudo-random inputs (Pew & Rupp, 1971; Wickens, 1976). In his summary paper of human tracking behavior, Adams (1961) stressed the importance of the use of gain and phase parameters as dependent variables in the same manner as root mean square error (RMSE), and urged for a rapprochement between the engineering and psychological disciplines.

The basis of the McRuer Crossover Model is that the human will adopt the most appropriate transfer function in order that the man-machine system behaves as a simple first-order servomechanism with an inevitable time delay (primarily due to human information processing, but also from machine dynamics and neuromuscular pathways). The open-loop man-machine transfer function ($Y_P Y_C$) at angular frequency ω (in radians) is simply,

$$Y_{OL}(j\omega) = Y_P Y_C = \omega_C e^{-j\omega \tau_e} / j\omega$$

Using this model McRuer and his colleagues have been able to account for 90% of the variance in compensatory tracking systems with low input bandwidths (Sheridan & Ferrell, 1974). That is, the Crossover Model is very accurate at describing the gain and phase of a man-machine system at the range of crossover, i.e., around the frequency at which the open-loop gain of the system is unity, or zero dB. Because the machine parameters are known from the controlled element dynamics used, the human gain and phase are easily extracted from the open-loop man-machine transfer functions.

It is these comprehensive studies that makes the tracking task suitable to laboratory analysis. Extensive data exist documenting human transfer functions for a wide variety of controlled element dynamics. Sheridan & Ferrell (1974) demonstrated that nearly identical human transfer functions have been derived by different researchers in different laboratories, in studies conducted 10 years apart.

C. Man-Machine System Design

Over the past three decades a substantial amount of literature has been collected on tracking performance in the evaluation of display, control, and dynamic configurations (eg., Chernikoff et al., 1960; Chernikoff & LeMay, 1963; Fracker & Wickens, 1989; Levison & Elkind, 1967). Numerous display, control, and dynamic configurations have been assessed for a variety of divided attention tracking tasks and subsequent recommendations have enabled system design engineers to develop efficient multi-task working environments (eg., cockpits). The work of Chernikoff and his colleagues mainly examined display-control configuration in a behavioral (RMSE) setting. Research by Levison & Elkind expanded upon the work of McRuer and his colleagues by proposing model requirements for dual-axis tracking with separated displays. This served to document the importance of foveal and peripheral "strategies" that have become useful in the consideration of human performance (Wickens & Liu, 1988). However, inconsistencies have surfaced between early studies and given rise to speculation regarding the optimal display-control configuration for certain task combinations. Fracker & Wickens (1989) provided a comprehensive replication of the work by Chernikoff et al. (1963) by incorporating control-theory and traditional psychological parameters in the examination of display,control, and dynamic homogeneity configurations, and were able to predict performance outcomes based on multiple resource theory and confusion theory.

Consistent design configurations have been determined for a dual-axis tracking task that has identical (homogeneous) tracking dynamics on each axis (Chernikoff et al., 1960; Chernikoff & LeMay, 1963; Fracker & Wickens, 1989). With this dynamic configuration it is advantageous to incorporate an integrated display (where the error for each axis is integrated into a single error cursor) with an integrated control (both axes are controlled with one hand/control). This configuration provides support for a compatibility of proximity hypothesis (e.g., Barnett & Wickens, 1988; Kramer et. al., 1985) which states that performance will improve if the proximity increases between processing stages. Compatibility is said to be high when the proximity between displays matches the proximity between controls.

Therefore, if displays are integrated (integrated at the perceptual stage) then controls should also be integrated (integrated at the response stage of processing). An example of an integrated display is the use of a vector to represent the status of two systems. An integrated control is an apparatus (stick, dial, etc.) which provides control for both systems by manipulation in different axes, directions, etc.

A middle stage of proximity exists; that which considers the central processing requirements of the task at hand. If two tracking axes are controlled with homogeneous dynamics, then they are assumed to require the same central processing operations since tracking in two axes with identical control dynamics is equivalent to performing two identical tasks at once. Therefore, it is suggested that dual-axis tracking of a system with homogeneous dynamics is proximally compatible with integrated displays and controls i.e., a display-task-control proximity exists with this configuration. An incompatible display-central processing proximity is demonstrated when a separated display (with two discrete representations) is combined with two tasks requiring identical central processing. It follows that configurations can also demonstrate display-control incompatibility, and central processing-control incompatibility.

A proximally compatible display-control configuration can be said to demonstrate a display-control integrity or S-R integrity. An S-R integrity configuration has proven to be advantageous for tracking with homogeneous dynamics and also with heterogeneous dynamics i.e., where the control dynamics of one axis differ from the control dynamics on the other (Chernikoff & LeMay, 1963; Fracker & Wickens, 1989). With heterogeneous control dynamics the control strategies required for the control of the two tasks is dissimilar and thus, compatibility of proximity hypothesis suggests that a separated display and separated control configuration would be advantageous. However, the above studies have been inconclusive as to whether the displays and controls should be integrated or separated when heterogeneous dynamics are present.

Does this indicate that the matching of the proximity at the central processing stage is not as important as matching the proximity between displays and controls? Indeed, the results of Fracker & Wickens (1989) demonstrated that the dual-axis error increased with separated displays if the control dynamics were the same but not if they were different. Although this finding is consistent with the compatibility of proximity hypothesis, the data indicated that the display-dynamics interaction may also be interpreted as a resource effect. With homogeneous dynamics the subjects were shown to attend to both axes equally and thus, the scanning requirement of the separated display was said to lead to an increase in tracking error. Because subjects biased there attention toward the acceleration axis in the heterogeneous condition it was argued that there was little chance for scanning to occur. Subjects periodically monitored the easier axis with peripheral vision while maintaining the acceleration axis in foveal vision. Therefore, the display-dynamics interaction was argued to be more likely a result of attentional strategies rather than compatibility of proximity between display integrality and tracking dynamics. This switching strategy is very similar to that described by Levison & Elkind (1967) in the evaluation of separated displays in dual-axis tracking. This finding could indicate that the compatibility of proximity hypothesis is a function of resource theory.

D. Predicting Performance for a Heterogeneous Tracking System

The display-control (S-R) integrity finding provides support for a confusion theory explanation of dual-task interference. Incompatible S-R configurations (Duncan, 1979) denote a different proximity at the perceptual and response stages of processing. This requires the subject to perform a mapping operation in order to make the incompatible outcome compatible. Without this mapping operation errors are likely to occur, and with the mapping operations subjects response times should increase. Confusions result as a consequence of improper mapping and are observable as cross-talk (Navon & Miller, 1987) between the control of the two axes. In the case of separated controls, control-stick confusion is also observed (Fracker & Wickens, 1989), where the movements of one control-stick are appropriate for the control of the opposite axis. It is also argued that mapping operations are resource demanding. Therefore, degraded performance with incompatible S-R configurations can be attributed to a scarcity of resources when performance is resource-limited (Navon & Gopher, 1979). Therefore, resource theory also predicts better performance when S-R integrity is incorporated in the system.

Compatibility of proximity hypothesis and confusion theory can be complementary when predicting performance with separated displays and separated controls for a system with heterogeneous tracking dynamics. Compatibility of proximity hypothesis argues that incompatible mapping operations are not required when separated displays are used for a dual-task which requires different central processing operations with each axis controlled by a separate hand (e.g., Boles & Wickens, 1987; Carswell & Wickens, 1987; Kramer et. al., 1985). That is, there is less chance of confusion between the heterogeneous axes if they are presented separately at the perceptual stage and controlled separately at the response stage.

Research in the motor behavior domain has provided evidence which could lead to conflicting predictions from confusion theory with respect to control configuration and the level of performance. Kelso, Southard, & Goodman (1979) have argued that each response hand defines separate channels within the motor control system, and reported degraded performance when separate hands must make incompatible movements. Klapp (1979, 1981) has explained similar findings in the context of temporal compatibility. Kelso et al. (1983) provided evidence that the entire synergy of movement with one hand can be contaminated by a more difficult, temporally incompatible movement with the other hand. As mentioned earlier, similar findings have been noted by Fracker & Wickens (1989) in dual-axis tracking where gain slopes indicated that the control for the easier tracking axis (velocity dynamics) became biased toward those of the higher order tracking axis (acceleration dynamics) when combined in a heterogeneous dynamics condition. Thus, movement of the easy control was contaminated by the movement of the hard control. Fracker & Wickens (1989) illustrated that subjects bias their attention toward the more difficult axis and also spend a greater proportion of time switching attention between the two axes than they do when homogeneous dynamics are employed.

However, since skilled performance does exist in situations with separated controls (eg., helicopter pilots), it is assumed that temporal incompatibility can be overcome with skill development (Kelso et al., 1979). To summarize, initial confusions may exist with separated controls for heterogeneous tasks, but there is evidence that these confusions are overcome as skills develop. Speculations on the requirements or stages of this developmental process are discussed later.

Factors such as those discussed by Kelso et al. (1979, 1983) and Klapp (1979, 1981) provide intuitive explanatory power for the conflicting findings between the studies of Chernikoff & LeMay (1963) and Fracker and Wickens (1989). The researchers in the earlier study found that separated displays coupled with separated controls were advantageous with heterogeneous dynamics. However, this study utilized a somewhat predictable (non-random) input for cursor movement in each axis and a within-subjects design. The later study provided a more fine-grained analysis using a between-subjects design, random-appearing disturbance functions, and more difficult system dynamics (with real-world applications). The results from this study showed no effect of control integrality i.e., separated controls were not advantageous when paired with separated displays and heterogeneous dynamics. The fundamental differences between these studies may indeed account for their conflicting results. The higher level of difficulty of the later study may have prevented the subjects from overcoming the temporal incompatibility between response hands.

Resource theory makes a different set of optimal display-control integrality predictions for tracking with heterogeneous dynamics. Separated displays are more resource demanding as they require the operator to visually scan back and forth during operation. This scanning is responsible for loading working memory and the perceptual system since the peripheral vision system possesses low acuity. Levison & Elkind (1967) documented a decrease in operator gain as the degree of separation grew between displays but did not show a difference in operator phase. Therefore, these findings indicate that resource demand is increased and performance decreases when it falls within the resource-limited region for the task combination (Navon & Gopher, 1979).

Resource theory predicts optimal control configuration somewhat differentially depending on which application of resource theory is considered. As stated earlier, incompatible S-R mappings demand more resources and therefore, if an integrated display is employed then an integrated control will demand fewer resources. However, a separated display-control configuration would also satisfy the predictions of the compatibility of proximity hypothesis. That is, the compatibility of proximity is optimal between the separated display, the different (separate) controlled element dynamics, and the separated axis controls. However, this gain in compatibility is a trade-off against the greater resource-demanding separated displays.

Another version of resource theory supports the separated configuration. Friedman et al. (eg., 1981, 1982, 1988) hypothesize that each of the two cerebral hemispheres has it's own independent pool of resources and thus, performance should be superior with separated controls. Because control for each hand is provided by a separate hemisphere there are more resources allocated to the control tasks when two hands provide control.

It seems clear that a series of explanations are available for predicting performance in a system with heterogeneous control dynamics. However, there remains an important consideration. Specifically, the identification of the factors which determine if, how, and when an operator is able to overcome temporal incompatibility when utilizing separated controls with heterogeneous tasks. Surprisingly, Fracker & Wickens (1989) were unable to provide a statistically reliable effect of dynamic heterogeneity for control-stick confusion (two controls) or axis cross-talk (one control). However, reliable differences existed between the integrality of displays and controls. Integrated controls led to greater axis cross-talk than did separated controls, and integrated displays led to greater control-stick confusion than did separated displays. With the above considerations in mind it was decided to provide an extensive examination of the heterogeneous tracking system.

E. Mental Workload Predictions

Mental workload research has long been influential in the development of theories on the limitations of human performance (eg., Gopher & Donchin, 1986; Knowles, 1963; Moray, 1967). Workload measures are extremely popular in operational settings although there appears to be no coherent theory of subjective perceptions of workload (Moray, 1982, Yeh & Wickens, 1988). According to Yeh & Wickens (1988) subjective measures reflect the demands imposed upon working memory which is influenced by the amount of time-sharing between tasks, the amount of information held in working memory, and the demand on perceptual and central processing resources per unit time. However, Wickens multiple-resource model postulates that dual-task performance is determined by the amount and efficiency of invested resources, time-sharing strategies, and the competition for common resources. Yeh & Wickens (1988) have demonstrated that these determinants are the reason that performance and subjective ratings often dissociate and they propose a theory of dissociation based upon a multiple resources model (1988). For example, as more resources are invested in a resource-limited task, performance improves while subjective workload ratings often increase.

III. Objectives

A. Statement of the Problem

It is suggested that a comprehensive study of dual-axis heterogeneous tracking could further the understanding of human capabilities under divided attention. The design of such a study follows logically from the research discussed in the preceding section. For example, display-control configurations that demonstrate S-R integrity have repeatedly led to superior dual-axis tracking performance when control dynamics are combined in either a homogeneous or heterogeneous manner. The compatibility of proximity hypothesis is supported when control dynamics are homogeneous, with integrated displays and controls leading to superior performance for the two identical tasks. However, neither a separated nor an integrated advantage has been found universally when control dynamics differ in dual-axis tracking. Therefore, it is suggested that heterogeneous dual-axis tracking again be studied in combination with separated and integrated displays and controls.

In an attempt to resolve the conflicting evidence for the superiority of integrated versus separated displays and controls (e.g., Chernikoff & LeMay, 1963; Fracker & Wickens, 1989), a comprehensive paradigm was utilized in order to examine a wider range of variables. Particularly, it is of interest to determine the effects of control-order interaction with display-control integrality. When studying compensatory tracking systems, control order is analogous to level of task difficulty. Compensatory tracking systems of pure orders (zero, first, second) are easiest to control when the control order is low (i.e., zero-order, first-order) (e.g., McRuer et. al, 1967, 1968; Poulton, 1974; Ziegler, 1968), except in very special situations (e.g., Wickens, 1986). The literature suggests that an advantage may exist with a separated display-control configuration with lower-order control systems (Chernikoff & LeMay, 1963) but not with higher-order control systems (Fracker & Wickens, 1989). If these findings can be replicated then perhaps a comprehensive model of divided-attention should incorporate task difficulty when describing performance in the dual-task paradigm. Performance data may also be used within a POC space in order to identify the effects of display-control integrality and control-order under different priority manipulations. As discussed earlier, priority manipulation and control-order may be seen to interact since a larger occupied POC space (larger decrements) has been observed by Vidulich and Wickens (1981). This effect should be replicated if the tasks chosen are not data-limited, and the additional effect of integrality should be observable within the POC framework.

The study was designed to measure the occurrence of confusions and provide support for both confusion and resource theories. Control theory parameters such as gain slope and phase intercept index the degradation of performance on a particular axis as contaminated by a more difficult axis. It was predicted that confusions, measured as cross-talk between axes, would account for much of the data. Fracker & Wickens (1989) demonstrated axis cross-talk and control-stick confusion as functions of either dynamic heterogeneity, display integrality, or control integrality. It is expected that dual-axis gain and phase data of the low-order control axis will be shifted in the direction of the gain and phase of the more demanding high-order axis. It is of interest to describe the magnitude of this contamination between the integrality and control order groups. It is also of considerable interest to determine if the effect of confusions are only observable with higher-order (difficult) control (Fracker & Wickens, 1989), much in the same manner as performance decrements are predicted in the POC space. It was anticipated that this study would provide the necessary conditions for the identification and qualification of separate resources i.e., greater resource availability with two-handed control.

Fracker & Wickens (1989) used effective time delay (τ_e) measures to provide evidence for mapping operations when display and control integrality were incompatible. That is, τ_e (analogous to RT) was shorter when S-R integrity combinations were used. This study might further the determination and magnitude of these mapping operations by utilizing effective time delay measures. Evidence for a stimulus-central processing-response mapping may be identified if τ_e is larger for subjects in the integrated S-R condition. That is, although S-R integrity exists between the integrated displays and controls, the compatibility of proximity hypothesis suggests separated tasks require a mapping operation necessary for processing. Conversely, non-different τ_e measures would provide an argument against the inclusion of central-processing mapping operations in the compatibility of proximity hypothesis. That is, if additional mapping operations are not time-consuming when task proximity is different from S-R proximity, where does this incompatibility surface at a performance level?

A final goal of this study is to provide subjective measures of workload from subjects in the experimental conditions and compare these ratings to their respective performance measures. If resource theory predictions are upheld for the performance variables used here then it would also be expected that the subjective measures would reflect dissociations based on resource models.

B. Hypotheses

Hypothesis 1: Display-Control Integrality

Separated conditions best satisfy the predictions of confusion theory, and are consistent with the compatibility of proximity hypothesis (separated displays, different control dynamics, separated controls). Multiple resource theories argue that more resources are available with two-handed movements (separated controls), but separated displays demand more resources than an integrated display. Based on the existing literature a separated advantage is expected.

Hypothesis 2: Control-Order and Integrality

Performance in the high-order separated condition may be limited by the temporal incompatibility and/or the contamination of the more difficult task (axis). It is anticipated that the subjects in the easy (low-order) separated condition will be less affected by the incompatibilities discussed above. If this prediction holds, an integrality by control-order interaction will be observed. That is, a separated advantage might only be obtained with low-order of control.

Hypothesis 3: Task Emphasis

It is expected that dual-axis tracking will be sensitive to task emphasis manipulations. Dependent measures will reflect this sensitivity with the highest performance when 75% of the effort is given to the measured axis. It is also expected that performance will be lowest when 25% effort is given, and performance with 50% (equal) effort will lie between the two differential priority conditions.

IV. Method

A. Subjects

Thirty-three subjects (29 male, 4 female) from the Simon Fraser community were participants in the experiment. One male subject did not complete the study. All subjects were right-handed and task-naive. Subjects were paid for their participation upon the completion of the experiment.

B. Apparatus

An IBM-AT computer was programmed to provide experimental control. The tracking display was generated on a 13.5 x 16.5 cm rectangle portion of a Mini-Micro EGA colour monitor. The compensatory display provided the difference between the input (disturbance) signal and the subject's (control) signal from the joystick at every sample interval. Three identical Advanced Gravis Analog Joysticks were modified to accommodate the Tecmar Labmaster A/D inputs. The two joysticks which provided control in the separated and single-axis conditions were locked in their respective axes. The integrated joystick was left to move freely in both axes. Deflections of the joysticks were measured at a resolution of about 1/500th of the movement radius. Joystick position was sampled at 50 Hz, which was also the frequency at which the tracking display was updated. The same computer was used to implement the computerized version of the NASA Task-Load Index.

C. Disturbance Functions

The input disturbance signals were different for each order of control used. The input signals were a sum of six digitally created sine waves of frequencies ranging from: 0.8727 - 6.545 radians/sec for second-order control, 1.309 - 7.854 radians/sec for first-order control, and 1.407 - 8.727 radians/sec for zero-order control. In hertz, all frequencies lie below 1 Hz ($\omega=2\pi f$), which is the effective input bandwidth of the human for tracking random-appearing inputs. The frequencies were selected from pilot studies in order to meet certain criteria. Most importantly, the frequencies allow the subject to track at a reasonable performance level given the constraints of the experiment, and secondly they fall within or around the region of cross-over i.e., the portion of the frequency spectrum where the human behaves in a linear manner. The frequencies selected conform well to the input bandwidth/crossover frequency relationships for pure-order control reported by McRuer & Jex (1967).

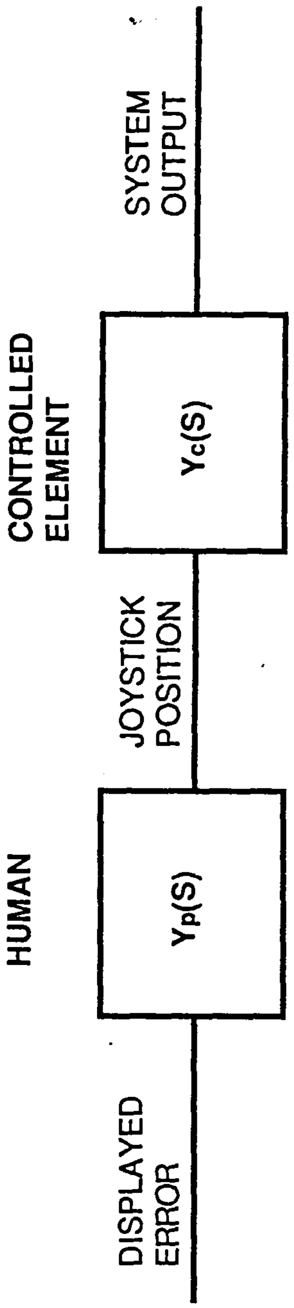
D. Display-Control Integrality

Displays and controls were either separated or integrated. When displays and controls were separated the following conditions were in effect. Error in each axis (horizontal and vertical) was displayed by a small (1cm) cursor ("--" & "|") that moved along its respective axis. With no deviation in either axis the two cursors formed a cross ("+") over the target in the center of the screen. Each cursor moved along its respective axis and did not move inside any quadrant of the display. Separated controls involved the use of two identical joysticks, one for the control of each axis.

Integrated displays and controls were used in the following manner. A single integrated display cursor represented the error in both axes. The cursor ("+") was free to move into any portion of the screen away from the target. Therefore, the subject perceived the error in both axes from the position of the cursor on the screen. Movement of a single joystick in the left-right axis controlled the cursor in the horizontal plane, whereas movement in the forward-back axis controlled the cursor in the vertical plane.

E. Control Order

Three pure orders of control were used and combined in two heterogeneous conditions of low and high control-order levels. The literature provides contradictory evidence (Chernikoff et. al., 1960; Chernikoff & LeMay, 1963; Fracker & Wickens, 1989; Ziegler, 1968] regarding which orders of control present the least, moderate, and greatest levels of difficulty. Thus, pilot testing was performed within the specific context of the experiment. Zero, first, and second-order dynamics were the pure-order dynamics evaluated during pilot testing. Zero-order control determines the position of the system (cursor) based on the joystick position. A first-order control system is a time integration system, denoted as a rate control system (McRuer, Graham, Krendel, & Weisener, 1965; Wickens, 1986), since the output rate of the system is proportional to the step input (joystick displacement). Second-order control is achieved through two time integrations of joystick position, thus controlling the acceleration of the system. Within the literature associated with tracking, it is conventional to call a zero-order control system a "position" system, a first-order control system a "velocity" system, and a second-order system an "acceleration" system (e.g., Wickens, 1986).The Laplace domain representation of the open-loop man-machine system is illustrated in Figure 3. This figure describes the requirements of the operator (Yp) to adopt the most appropriate transfer function in order for the man-machine system (YpYc) to behave as a simple first-order system with an inevitable (human) time delay. Therefore, the behavior of the operator (Yp) is determined by the controlled element dynamics (Yc) in order for YpYc to remain constant .



$Y_pY_c(S) = \frac{Ke^{-\tau_e S}}{S}$ OPEN-LOOP MAN-MACHINE SYSTEM: FIRST-ORDER SYSTEM WITH GAIN K AND TIME DELAY τ_e

CONTROLLED ELEMENT DYNAMICS & PREDICTED OPERATOR RESPONSE

$Y_c(S) = K_c$ (ZERO-ORDER) $Y_p(S) = (K_pe^{-\tau_e S})/S$ (FIRST-ORDER WITH DELAY)
$= K_c/S$ (FIRST-ORDER) $Y_p(S) = K_pe^{-\tau_e S}$ (ZERO-ORDER WITH DELAY)
$= K_c/S^2$ (SECOND-ORDER) $Y_p(S) = K_pSe^{-\tau_e S}$ (MINUS FIRST-ORDER WITH DELAY)

Figure 3- Laplace Domain Representation of Open-Loop Man-Machine System.

Based on results from pilot testing the control orders were paired in the following manner in order to construct the two levels of control order (task difficulty). The low-order condition incorporated the two lower-order dynamics: position and velocity. The high-order condition incorporated the two higher-order dynamics: velocity and acceleration.

F. Task Emphasis

Emphasis was controlled by providing a concurrent status of performance to the subject and also by utilizing a weighted pay-off scheme based on performance. Therefore, subjects were paid for their performance on each axis based on a differential bonus system. Three emphasis weightings were used: 50/50, 25/75, 75/25. Qualitative knowledge of performance (KP) was provided by the colour of the error cursor as it deviated from the target position. When the deviation reached a critical amount (defined by the emphasis condition in effect) the cursor colour changed from green to red.

The 50/50 condition was referred to as the equal-emphasis condition as subjects were instructed to control error on each of the two axes with equal emphasis on each axis. Subjects received equal bonus points based on their performance on each axis.

The 25/75 and 75/25 weightings were implemented to examine performance trade-offs between the tasks and conditions. The axis which received 75% of the subject's effort was referred to as the primary-axis. The axis which received 25% of the subject's effort was the secondary-axis. In the 25/75 condition the KP was structured such that the colour change occured for twice the deviation needed with the 50 weighting. Conversely, the warning for the axis with the more difficult control dynamics would show when half the deviation of the 50 weighting was detected. In the 75/25 condition the respective axes which were emphasized were switched.

When the 25 weighting was in effect for a particular axis the subjects were instructed that the bonus points received for controlling that axis were 1/3 of that for controlling the axis with the 75 weighting (i.e., 1/2 of the 50 bonus). However, subjects were also instructed that no bonus points would be given if their performance on the "25" axis was not at least 33% of their mean "50" performance. This helped prevent subjects from optimizing a maximum gain strategy by completely ignoring the "25" axis. Therefore, equal emphasis trials were completed before the differential emphasis trials and this criterion score was calculated individually and utilized during differential emphasis trials.

G. Dependent Variables

Several dependent variables were measured to provide a test for the above hypotheses. The variables chosen were expected to correlate with performance changes in RMSE (Wickens & Gopher, 1979). These authors found correlations between RMSE and gain, effective time delay, and response hold frequency which were studied here. Other control-theory parameters were also examined in an effort to document the existence of confusions between axes and/or joysticks. The control theory parameters described here were determined by using the formulae presented by Shirley (1969). A modified FFT algorithm was used to calculate the transfer functions of the human operator and man-machine systems. These calculations were made virtually "on-line" and gain and phase calculations were complete before the beginning of the next trial. Factors such as sampling frequency, disturbance input frequency, and trial duration were chosen in order to accommodate these analysis procedures. The variables are now defined.

i) Root Mean Square Error (RMSE)

RMS tracking error was measured as the square root of the sum of 10,800 squared deviations (216 sec x 50 samples/sec) divided by the total number of squared deviations. This measured the displacement of the display cursor(s) from the target position and provided a performance score for the subject.

ii) Control Speed

Control speed measurements describe the amount of control given to each tracking axis (Wickens, 1976) and provide an indicator of resource availability (Wickens & Gopher, 1977). In order to provide control speed measures the joystick position was sampled at 25 Hz with the sum of the deviations averaged at the end of each trial to yield a deviation per unit time measure.

iii) Gain Intercept

The gain of the human describing function is defined as the ratio of the operator's output relative to the driving signal and thus provides a measure of sensitivity. Gain intercept served as an overall index of gain since gain versus log ω was highly linear. Gain intercept measures are similar to control speed measures in that they describe the amount (or amplitude) of control on each axis.

iv) Gain Slope

Gain slope is simply the slope of the linear gain function (dB vs. log frequency) measured for the operator. This measure is useful for identifying motor cross-talk or confusions in responses. In order for the man-machine system to maintain the properties of a first-order servo-control system (McRuer et al., 1965) the human must adopt an appropriate control strategy (transfer function) in combination with the controlled element transfer function. For example, in order to meet the -20 dB/decade gain slope requirements of the first-order servo, the human must adopt a flat control strategy (gain slope of 0 dB/decade) when velocity dynamics are present (controlled element gain slope = -20 dB/decade). A positive gain slope of 20 dB/decade is predicted to offset the -40 dB slope of the acceleration control dynamics whereas a -20 dB slope is predicted for the human when a 0 dB gain slope for position is controlled.

v) Phase Intercept

Phase measures reflect how the operator's output signal lags (or leads) the input signal. Phase intercept is useful for examining the effect of confusions in much the same manner as gain slope. The human must adopt a particular phase strategy in order to offset the phase of the controlled element with the end result being a -90 degree phase intercept for the combined man-machine system. This effect is most often realized when velocity control is present. Phase advance (higher than expected intercept) is often noted with position control and phase droop (lower intercept than expected) is common with acceleration controlled elements (McRuer et al., 1965; McRuer & Jex, 1967; Shirley, 1969).

vi) Phase Slope

Phase slope is measured as the slope of the linear phase function (degrees vs. frequency) and provides a measure of the subject's effective time delay (τ_e) which is a measure analogous to reaction time (Pew & Rupp, 1971; Wickens, 1976; Wickens & Gopher, 1977). As mentioned previously, τ_e represents the balance of internal processing delays at the central stage and neuromuscular level, and lead time constants representative of the subjects' ability to anticipate the track in order to overcome delays produced by the controlled element dynamics (McRuer, 1980; Pew & Rupp, 1971).

vii) Response Hold

Response holds indicate when the subject is not exerting control over the system. A response hold was defined as zero deflection from the center position of the joystick i.e., an output signal of zero. Response holds are useful in determining when the subject is forced to use a serial response strategy in the dual-axis tracking task (Wickens & Gopher, 1977). Response holds were summed for each axis and presented as the number of zero samples detected.

viii) NASA Task-Load Index

The NASA Task-Load Index (Hart & Staveland, 1988) was used to collect subjective workload assessments in this study. This index has been developed as the result of extensive pilot-studies conducted through the NASA-Ames Research Center and is becoming a preferable choice for the measurement of workload in operational settings (eg., Hancock, 1989). This index was administered to subjects during the experiment to determine the effect of integrality and control order on mental workload. It was chosen to implement the Index after the equal-emphasis dual-axis trials were completed due to the time constraints already imposed on the subjects. The Index provides the relative importance (weight) of six variables: mental demand (MD), physical demand (PD), temporal demand (TD), effort (EF), performance (OP), and frustration level (FR). Each of these subscales are given a rating from 0 - 100 indicating low to high demand (except the OP rating where good performance is indicated at zero). Ratings are given on a linear rating scale generated on the computer display, and range from 0 to 100 with 1/20th intervals. The six subscales are weighted with respect to each other using 15 pairwise comparisons where the subject is asked to compare any two subscales with one another and identify the more important contributor to workload. The ratings are then combined with the weights to determine an overall workload rating for the subject. Therefore, the workload weights range from 0 to 1. The weights and ratings are then combined to yield a weighted workload rating for the subject. This score can range from any integer between and including 0 to 100. The weights and ratings from each subscale, along with the overall workload ratings were compared for the integrality and control-order conditions.

H. Knowledge of Results

Subjects received the RMSE score for each axis, along with the number of bonus points earned, and the highest bonus earned by any subject in that condition. This information was displayed on the computer screen immediately following each trial. The bonus score was directly proportional to the single-axis error for single-axis trials, and to the error in both axes (radial error) for the dual-axis trials. Subjects who earned the highest bonus for each of the three single-axis conditions: zero-order, first-order, second-order; and the twelve dual-axis conditions (2 integrality x 2 control order x 3 emphasis) received an extra monetary bonus for their performance(s). It was anticipated that the knowledge of this reward and the high score display motivated subjects throughout testing. Fracker & Wickens (1989) reported positive results with a similar methodology.

V. Procedure

A. Design

The experimental design used to test the hypotheses of the proposed research entailed two between-subject variables and one within-subject variable. The first between-subject variable was display-control integrality. There were two levels of this variable: integrated and separated. The second between-subject variable was order of control. There were two levels of control order: low and high representing low and high levels of task difficulty. Subjects were randomly assigned into four separate groups.

The within-subject variable was task emphasis. Three levels of task emphasis were used in the present study: 50/50, 25/75, and 75/25. These represent equal subjective effort on both tracking axes, one-third effort on the velocity dynamic axis, and one-third effort on the position (low-order) or acceleration (high-order) dynamic axis respectively.

B. Protocol

One female and seven male subjects were randomly assigned to one of the four display-control integrality, and control-order conditions. Also, subjects were randomly balanced for hand assignments within their respective condition. (Because first-order control was used in both control-order conditions it is easiest to describe the axis which is assigned this type of control.) Subjects in the integrated conditions were randomly assigned to the use of either their left or right hand throughout the experiment and first-order control was balanced between the two axes. Subjects in the separated conditions were randomly assigned to either a left hand-horizontal axis / right hand-vertical axis or left-vertical / right-horizontal condition. Again first-order control was split between the two axes. Finally, the order of presentation of control dynamics was balanced within each group such that half of the subjects learned (and emphasized) the axis with velocity control first. Therefore, each of the four groups of interest (integrality x control-order) were sectioned into four balanced groups to balance effects of response hand, tracking-axis (horizontal or vertical), and order. This procedure is recommended by Poulton (1974).

The experimental design and protocol is illustrated in Table 1. Each session of the experiment summarized in Table 2. Testing was carried out over three sessions and took place in a light and sound attenuated environment with only the subject and experimenter present. Subjects were asked to complete the experiment in three successive days. Each session of testing required the subject to partake in a number of single and/or dual-axis tracking trials. Each trial consisted of 216 seconds of tracking. This trial duration was used to ensure that the low frequency components of the input signal were identifiable during data analysis and accommodated the fast fourier transform (FFT) algorithm (Shirley, 1969) used to determine the human gain and phase functions. Trials were separated by one minute rest periods.

Subjects completed single-axis tracking trials for each of the control dynamics in the first session of testing. There were eight trials of tracking in each axis. Four trials on each axes were completed twice. One-minute rest periods were given after every trial, and one three-minute break was given in the middle of testing. This session of testing was completed in about eighty minutes.

The second session was primarily used for dual-axis practice and trials in the equal-emphasis (50/50) condition. Subjects began the second session by completing one single-axis trial in each axis. Three equal-emphasis dual-axis trials were then performed followed by a 3-minute break. One single-axis trial was then performed on each axis to enable a check on single-axis baseline measures. Three more dual-axis trials followed by a three-minute break were then completed. Tracking for this session was then completed with four more dual-axis trials. Following testing, subjects were asked to complete a computerized version of the NASA Task-Load Index which required about 15 minutes. The second session required a total of 90 minutes.

The final session was used to collect data for the differential task emphasis conditions. A single equal-emphasis (50/50) trial provided a warm-up for the subjects. Subjects were then instructed on the emphasis-bonus structure to be employed for each differential emphasis condition.

Table 1- Hand, Axis, Order Assignment for Subjects in Integrality x Control-Order Conditions

CONTROL-ORDER	INTEGRALITY	
	INTEGRATED	SEPARATED
	HAND,AXIS,ORDER	HAND,AXIS,ORDER
LOW	S1-L,H,1	S17-
	S2-L,H,2	S18-
	S3-L,V,1	S19-
	S4-L,V,2	.
	S5-R,H,1	.
	S6-R,H,2	.
	S7-R,V,1	.
	S8-R,V,2	S24-
HIGH	S9-L,H,1	S25-
	S10-	S26-
	S11-	S27-
	.	.
	.	.
	.	.
	.	.
	S16-	S32-R,V,2

HAND- (Left,Right) Denotes the hand which was assigned to the axis with velocity control dynamics.

AXIS- (Horizontal, Vertical) Denotes the axis which was controlled with velocity dynamics.

ORDER- (1,2) 1 identifies subjects which learned tracking in the velocity axis first, 2 denotes either position (low-order) or acceleration (high-order) trials were performed first.

Table2- Summary of Protocol by Session

	SESSION	DESCRIPTION
1	Single-axis tracking in each axis.	
2	Dual-axis tracking with equal effort on both axes. NASA-TLX implementation.	
3	Dual-axis tracking with differential-emphasis conditions.	

Two dual-axis emphasis trials (e.g., 25/75) were preceded by a single-axis trial of the emphasized axis (75) followed by a break and repeated for the other emphasis condition (in this case 75/25). After a break each differential emphasis condition was again repeated 3 times followed by another break. The session concluded with a final single-axis trial preceding a final differential emphasis trial on that respective axis. The final session required about 85 minutes, bringing the total time required per subject to approximately 4.5 hours.

C. Data Collection

RMSE, control speed, and response-hold data were collected for every trial. On-line data from the human input-output, and system output were used for control theory analysis. These data were collected during the following trials: the final three single-axis trials for each axis in Session 1; the last single-axis trial for each axis, and the final five equal-emphasis dual-axis trials in Session 2; and the last single-axis trial for each axis, and the final five differential-emphasis dual-axis trials in Session 3. Therefore, 20 of the 47 trials were used in the data analysis, 5 single-axis trials and 5 dual-axis trials in each emphasis condition.

Mental workload data were collected using the NASA Task-Load Index after the completion of the tracking trials of the second session. Subjects were asked to assess the demands of the equal-emphasis dual-axis tracking trials which they had just completed. Subjects provided ratings and weights for each of the subscales by responding to the computerized version of the Index. The ratings and weights were then combined to provide an overall workload rating.

VI. Results

The results section is divided in the following manner. First, the section is divided into two parts, tracking data and mental workload data. The tracking data is discussed in terms of each dependent variable i.e., RMSE, control speed, gain intercept and slope, phase intercept and slope, and response hold. Second, the mental workload data are divided into components specific to the NASA TLX-Index, i.e., weighted workload ratings, raw workload ratings, and raw workload weights.

A. Tracking Data

Initially, single-axis velocity RMSE data were analyzed to determine if any of the four groups (2 integrality x 2 control-order) were biased with respect to subjects of inferior or superior tracking ability. A 2 x 2 ANOVA indicated that the single-axis RMSE scores did not differ between integrality (p=.223) or control-order (p=.735), nor did they interact (p=.839).

The dual-axis data were examined in the following manner. Since all subjects completed tracking trials with velocity control on one axis a global analysis (2 integrality x 2 control-order x 3 emphasis) could be performed on the velocity data. For the data from the position and acceleration axes, a 2 x 3 (integrality x emphasis) analysis was used. Data were never combined from two separate control dynamics in the same analysis. The Hyunh-Feldt correction factor was used to adjust the degrees of freedom for the repeated measure (emphasis) effects. Tukey's HSD test was chosen to make comparisons between means for emphasis main effects and any interactions. This conservative test was used in an attempt to guard against escalating family-wise error rate for the global analyses described here.

Two dual-axis data analysis procedures are presented. The first is the simple analysis of the raw dual-axis data to determine performance differences between the experimental variables. The second analysis used dual-axis decrement scores to determine the extent of interference that the concurrent axis had on the analyzed axis. In order to use dual-axis decrement scores effectively stable single-axis baselines were required.

In this experiment stable single-axis baselines were determined by analyzing the single-axis scores from the first session against the single-axis trials from the second and third sessions (after dual-axis trials had been performed). A well documented effect in the literature is that dual-axis tracking produces a carry-over effect to single-axis gain measures (Damos & Wickens, 1980; Fracker & Wickens, 1989). This effect was replicated for the gain intercept and gain slope measures in this experiment ($p<.05$). That is, single-axis gain intercepts were shifted upward and single-axis gain slopes were biased toward the gain slope of the concurrent axis, after dual-axis trials had been performed. Also, the single-axis RMSE and control speed scores were affected by the dual-axis trials ($p<.05$). Since RMSE was affected in a consistent direction for each condition, a special condition is described later for the analysis of the RMSE decrements Not surprisingly, the single-axis control speed data reflected similar changes as the gain intercept measures and therefore were not subject to decrement analysis. The response hold and phase data were amenable to decrement score analysis. Because the within-subject effects are identical for both types of analysis (raw dual-axis data and decrement scores) decrement scores are only discussed in terms of the between-subject variables i.e., control-order and integrality, but not emphasis.

Bode plots represent the human transfer functions. The transfer functions are represented by a gain and a phase at each input frequency. Bode plots represent gain in decibels, and phase in degrees, plotted against the logarithm of frequency. Because gain is linearly related to log ω and phase is linearly related to ω , least squares approximation can be used to determine gain and phase intercepts and slopes. First-order polynomials were fit to the gain and phase plots in order to determine intercepts and slopes for the functions. The following procedure was used to fit the polynomials to the data. It was decided to fit the data in the region of crossover i.e., that range of frequencies where the human behaves in a highly linear manner (McRuer et. al., 1965; Sheridan & Ferrel, 1974). That is, not all frequencies present in the input signal are amenable to simple linear analysis procedures. Extremely low frequencies were placed in the input signal to lower the effective bandwidth of the signals.

Simple first-order polynomials represented the gain (dB vs. log frequency) and phase functions (degrees vs. frequency). For the velocity gain function, all six frequencies present in the input signal were used. For the phase function, the five highest frequencies were selected in order to avoid non-linear "phase droop" at extremely low frequencies (McRuer & Jex, 1967). The position gain and phase data were examined at the four highest frequencies in the input signal. For the gain function this was the region beyond the operator lag-equalization break-point i.e., the region where the operator no longer uses an anticipatory lead and adopts a linear control strategy. Similarly, this lag-equalization was evidenced in the phase data as "phase advance" at the lower frequencies. Finally, the acceleration gain data were examined at the five highest frequencies and the phase data at the four highest frequencies in order to disregard phase droop at regions below crossover (McRuer & Jex, 1967). The Bode plots illustrate all input frequencies and demonstrate the effects described above. The curves are fitted to the frequencies outlined above. (It should be noted that the lowest input frequency of the acceleration Bode plots is not shown because it lies below 1 radian/second and would only serve to diminish the region of interest. Such is the nature of logarithmic scales).

A glossary of abbreviations is provided in Appendix A. ANOVA tables are provided in Appendix B.

i) RMSE

The results for the velocity RMSE data indicated that there was a significant effect of integrality (p=.012) with the integrated conditions performing better than the separated. Also, the effect of emphasis was significant (p<.0001). Tukey's HSD test indicated that the velocity-emphasis condition was significantly better than the equal-emphasis condition which was in turn better than the position/acceleration emphasis condition (p<.01). These effects are shown in Figure 4. (RMSE measures are shown in units of the display screen). There were no other significant effects for the velocity RMSE data.

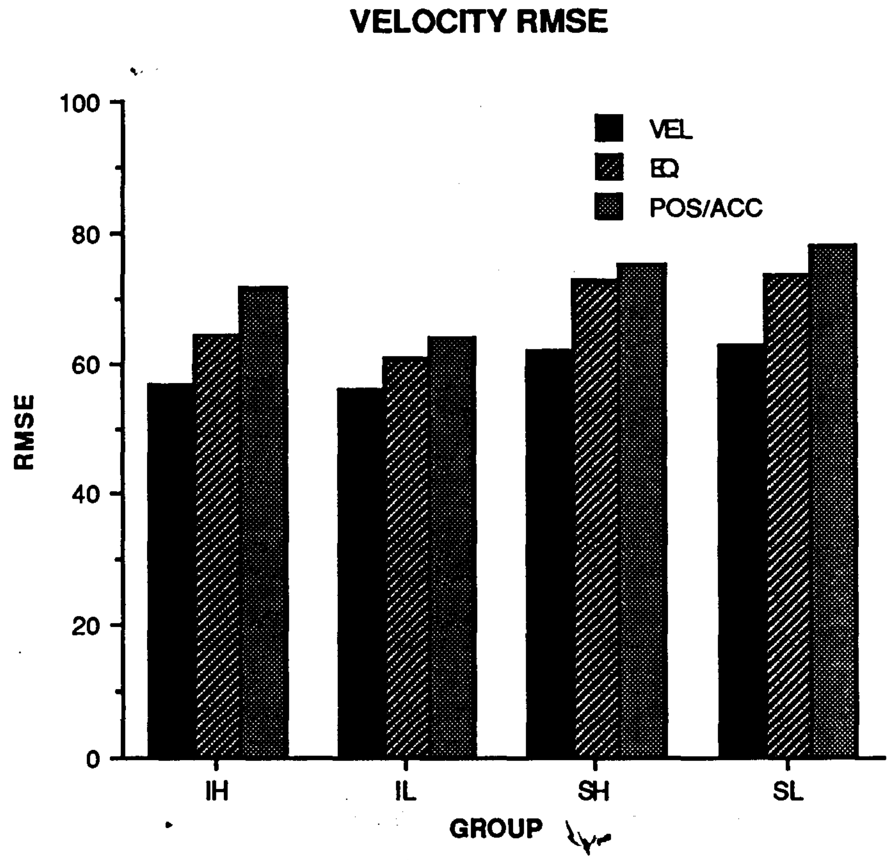


Figure 4- Integrality and Emphasis Main Effects for Dual-axis Velocity RMSE.

The position RMSE analysis replicated the velocity RMSE results with a nearly significant integrality main effect (p=.050) and a significant emphasis main effect (p<.0001). Again the integrated condition showed better RMSE scores. Pairwise comparisons indicated that again the three emphasis conditions differed significantly from one another (p<.05), and in the expected direction (primary<equal<secondary). Figure 5 illustrates these effects. There was also a significant emphasis x integrality interaction (p=.021). For the integrated condition the primary and equal-emphasis means differed from the secondary but not from each other, whereas in the separated condition the equal and secondary means differed from primary but not from each other (p<.05). This interaction can be seen in Figure 6.

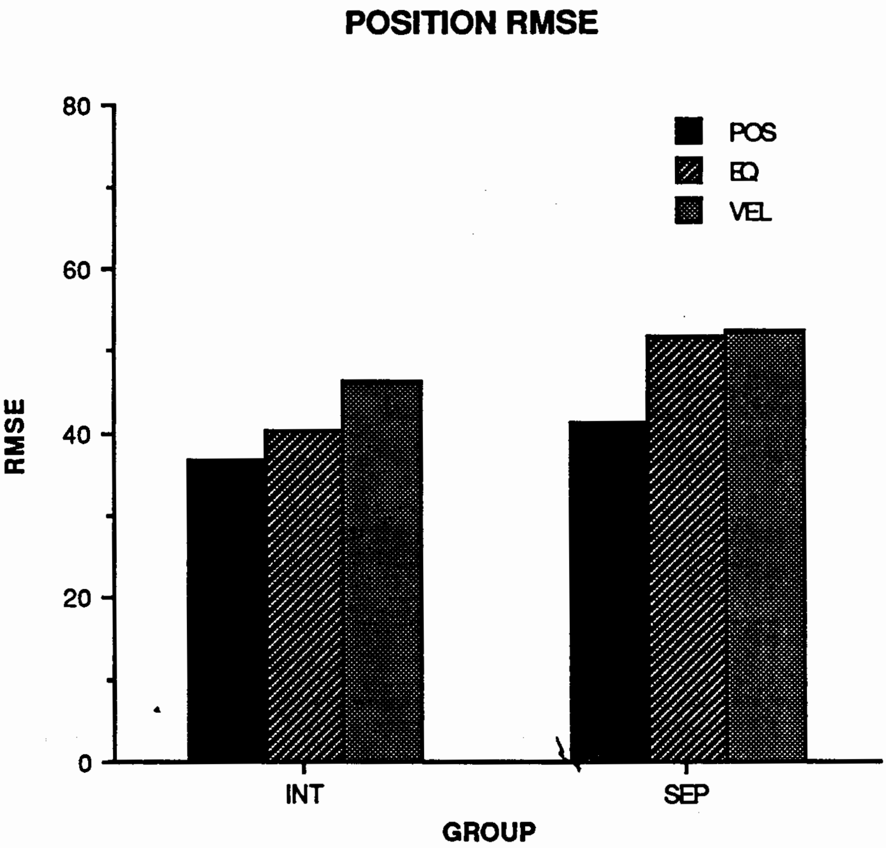


Figure 5- Emphasis Main Effect for Dual-axis Position RMSE. (The integrality main effect approached significance [p=.050]).

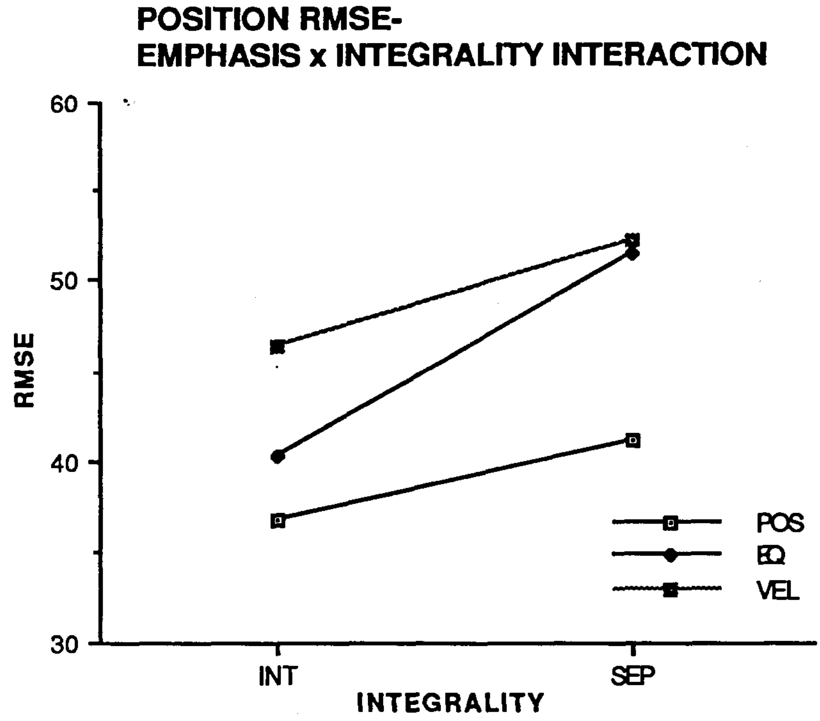


Figure 6- Emphasis x Integrality Interaction for Dual-axis Position RMSE.

The acceleration RMSE analysis showed significantly better performance for the integrated condition (p=.034). The emphasis main effect was again strong (p<.0001) with all means differing significantly and in the expected order. Figure 7 illustrates that the equal emphasis means were closer to the secondary (velocity) emphasis means (p<.05) but farther from the primary (acceleration) emphasis means (p<.01). The emphasis x integrality interaction was not significant (p=.484).

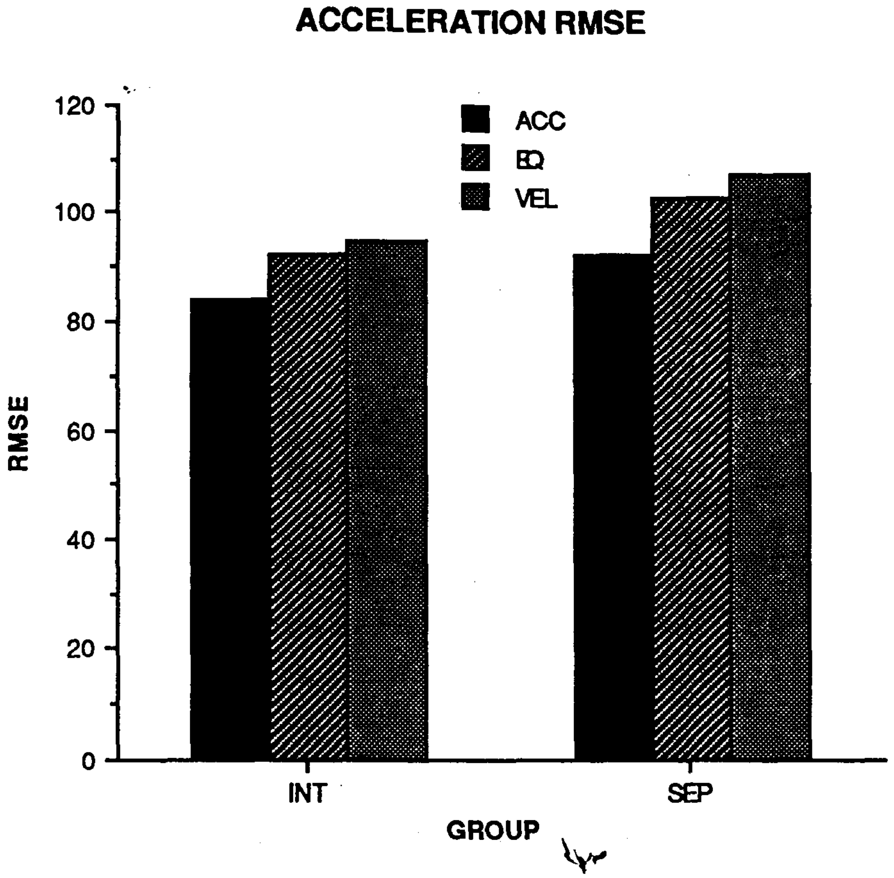


Figure 7- Integrality and Emphasis Main Effects for Dual-axis Acceleration RMSE.

RMSE performance is illustrated in a POC setting in Figure 8. (Note that better performance is represented near the origin due to the nature of the RMSE variable). The emphasis scores are plotted relative to the single-axis scores for each condition. That is, the dual-axis decrements are used to illustrate time-sharing efficiency among the groups. It will be recalled that time-sharing efficiency is expressed by the proximity of the POC to the single-task performance region. As mentioned earlier, single-axis RMSE results showed significant improvement as a result of dual-axis trials for all conditions. It was decided to use the mean of the final two single-axis trials as most representative of final single-axis performance. RMSE decrement analyses replicated the control-order and integrality effects noted in the raw data analysis. That is, larger decrements for the velocity data were noted for the separated conditions (p.=.016). Also, larger RMSE decrements were found for the separated position (p=.035) and acceleration conditions (p<.001).

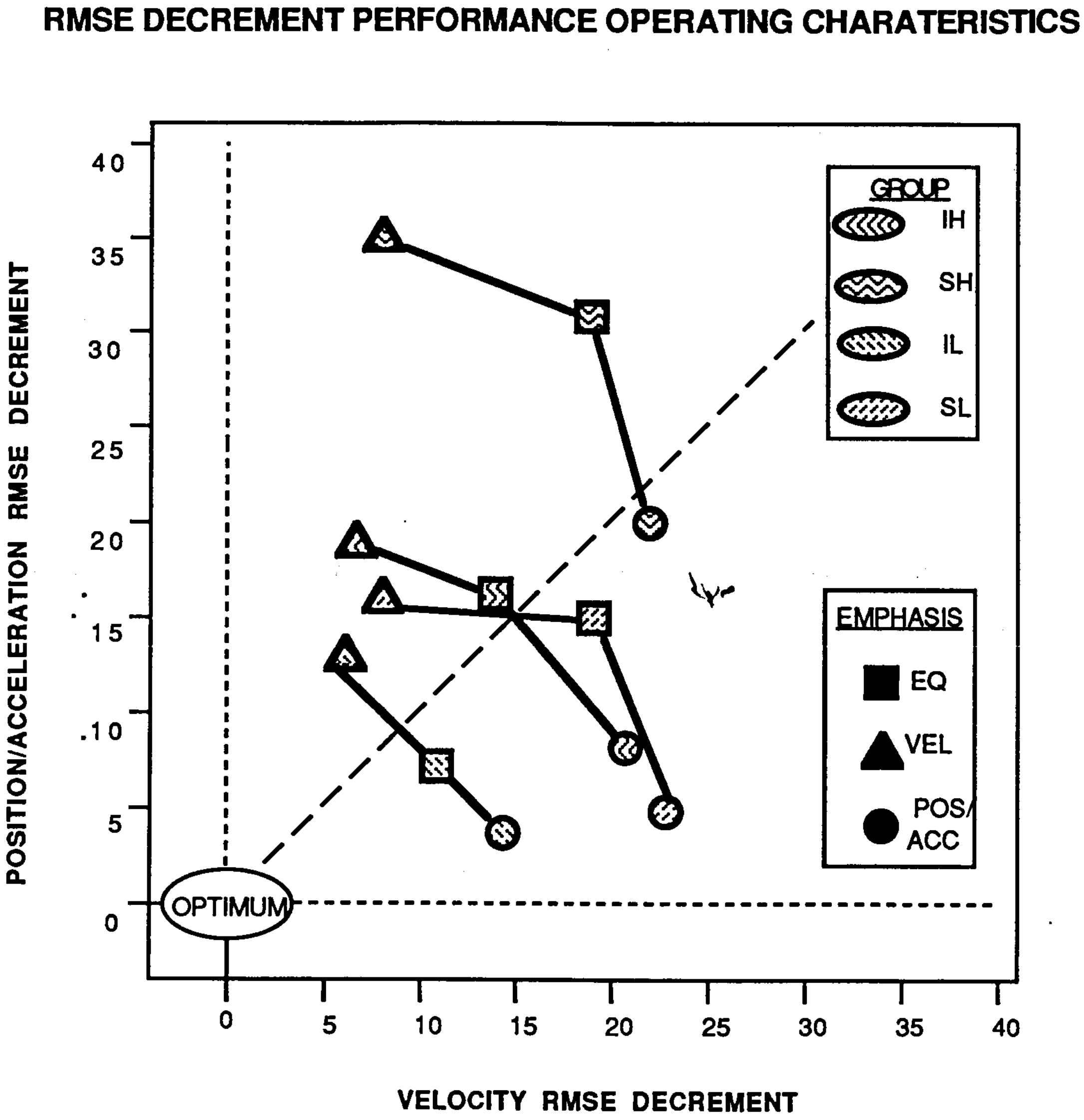


Figure 8- RMSE Decrement POC's for Integrality and Control-Order Conditions.

Performance trade-offs were examined to determine the effects of integrality and control-order. Performance trade-offs were quantified as the difference between the two extreme emphasis RMSE means for each axis. The timesharing efficiency results were not replicated with significant trade-off differences. Neither the integrality or control-order effects approached significance for the velocity data (p=.437, p=.366). Significant integrality effects were not realized with the position (p=.592) or acceleration (p=.592) data.

ii) Control Speed

Figure 9 illustrates a significant effect of integrality for the velocity control speed data (p=.026) with the separated condition using higher control speeds than the integrated condition. (Control speed measures are given in units of joystick position per sample time). The control-order x integrality interaction approached significance (p=.051) suggesting there was possibly a larger difference between the integrated and separated conditions for the high-order condition. This effect is illustrated in Figure 10. The emphasis main effect was again strong in the expected order (p<.001). Tukey HSD comparisons indicated that the control speed for the secondary-emphasis condition was significantly lower (p<.05) than that for the equal and primary conditions which did not differ.

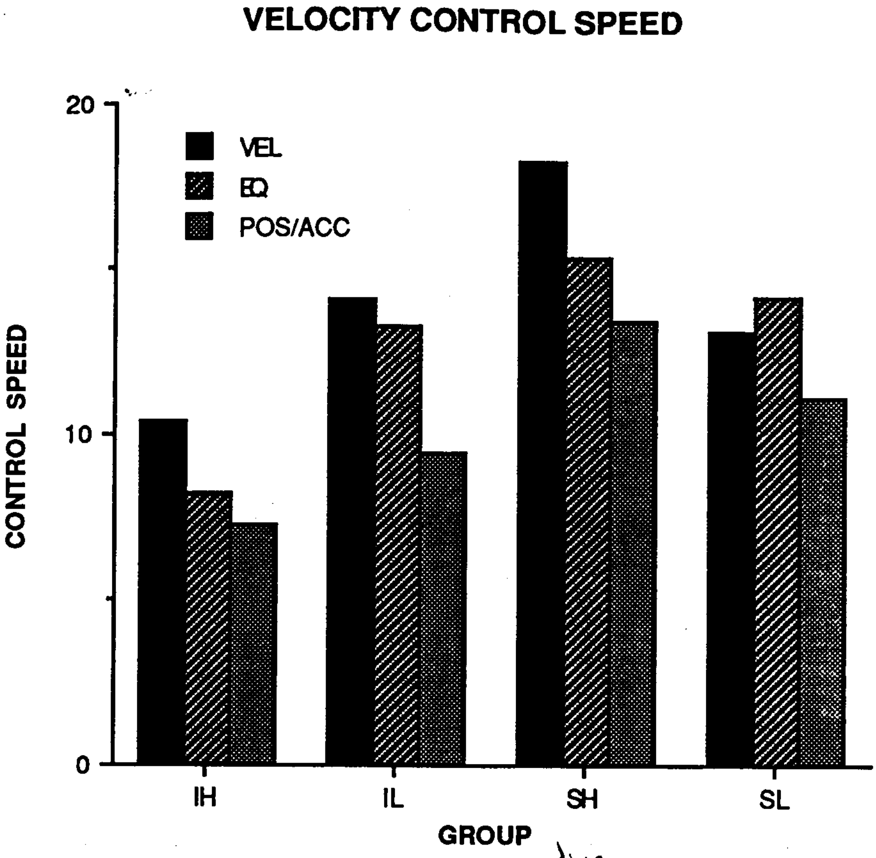


Figure 9- Integrality and Emphasis Main Effects for Dual-axis Velocity Control Speed.

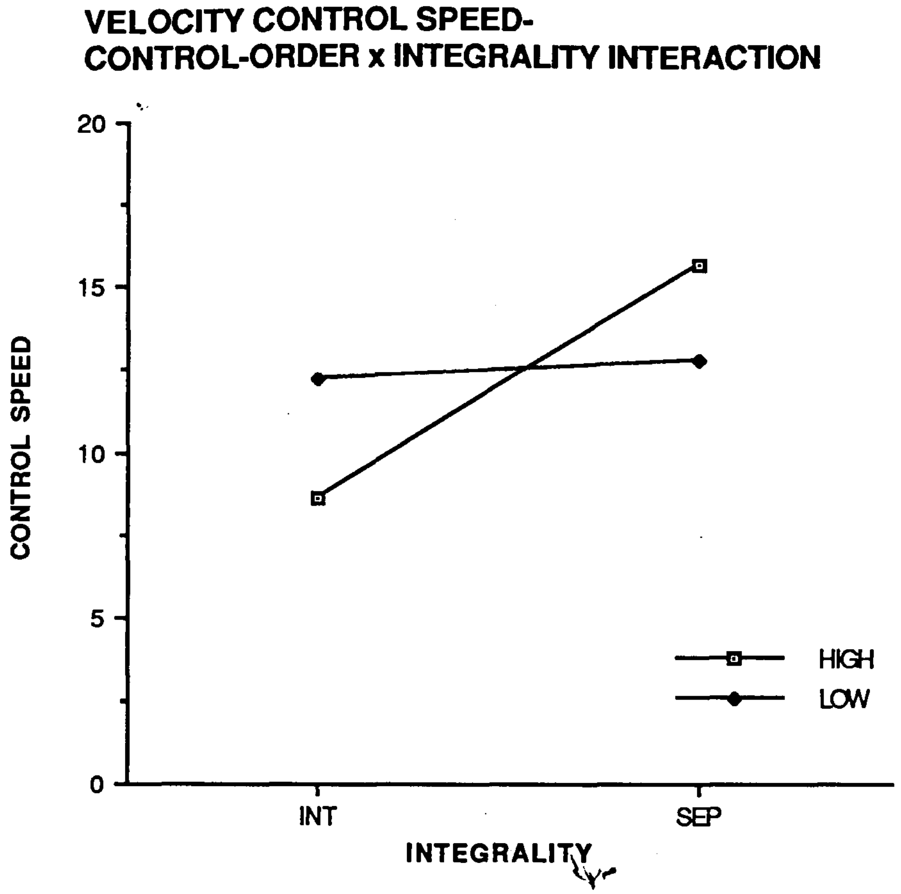


Figure 10- Control-order x Integrality Interaction for Dual-axis Velocity Control Speed.

The mean position control speed for the separated condition was not significantly larger than the integrated condition (p=.52). The emphasis main effect was again evident and in the expected order (p=.010). This effect can be seen in Figure 11. The velocity-emphasis mean was significantly less (p<.01) than the equal and position-emphasis means, which did not differ.

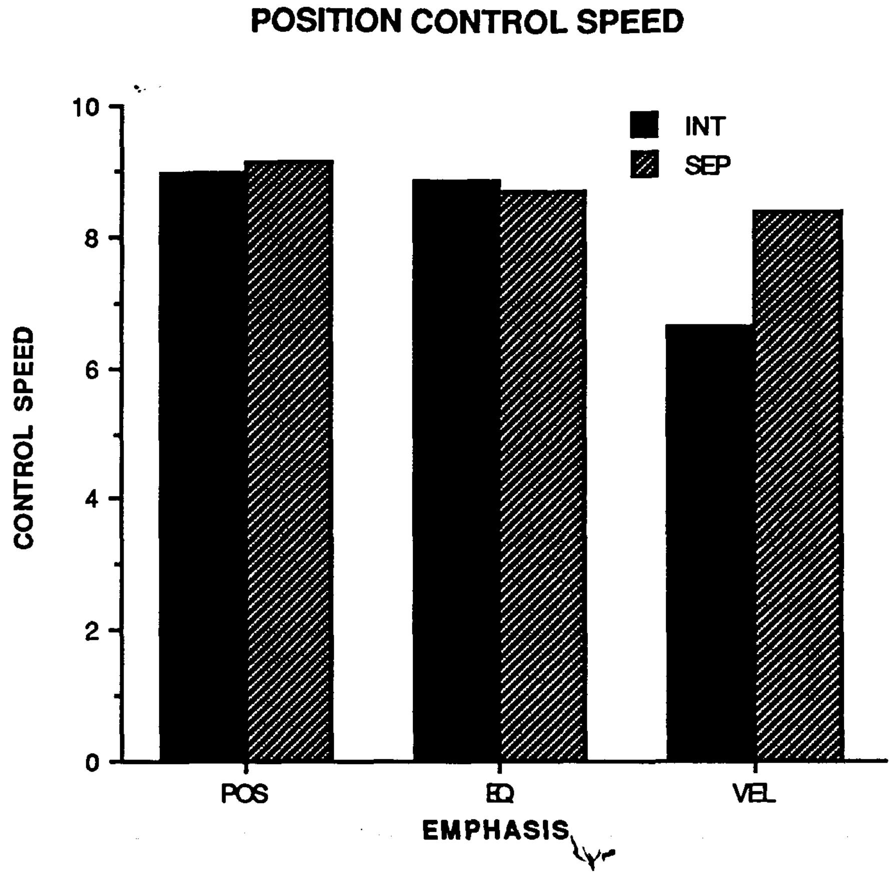


Figure 11- Emphasis Main Effect for Dual-axis Position Control Speed.

The integrality effect was significant for acceleration control speed (p=.021) with the separated group producing quicker control movements. The emphasis effect was present and in the expected order (p=.024) with the velocity-emphasis mean significantly slower (p<.05) than the other two means which did not differ. These effects are shown in Figure 12. The emphasis x integrality interaction approached significance (p=.058) indicating that the separated condition may have been affected to a larger extent by the emphasis manipulation.

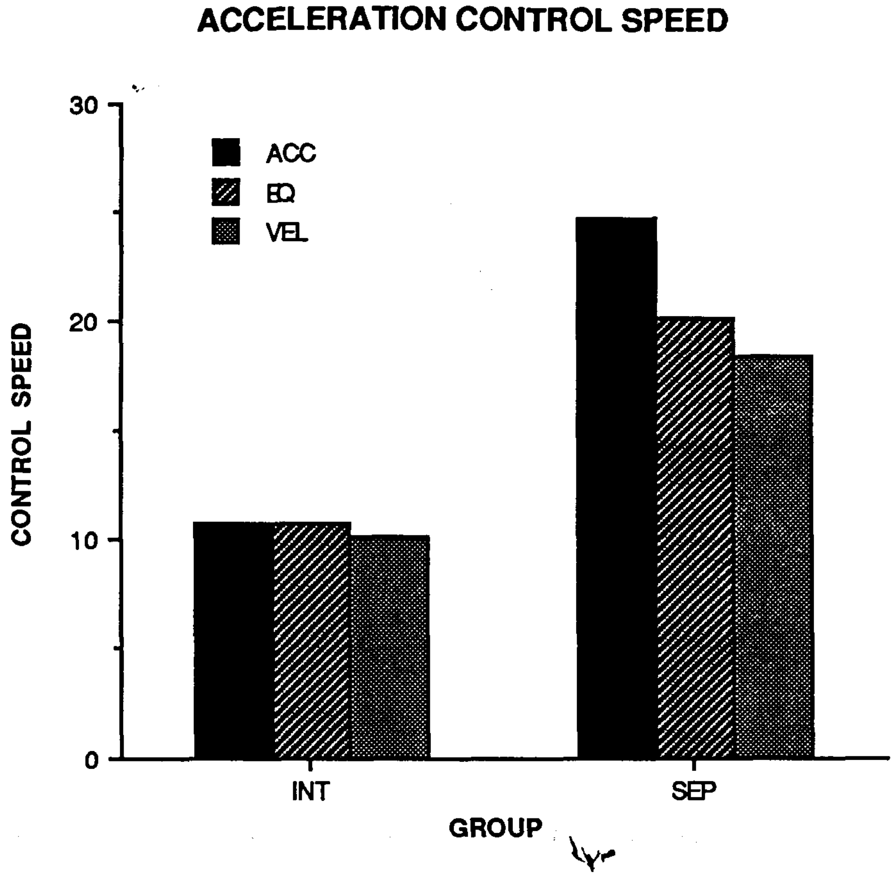


Figure 12- Integrality and Emphasis Main Effects for Dual-axis Acceleration Control Speed.

iii) Gain Intercept

Bode plots for velocity data are shown in Figures 13 through 16. There was a significant control-order effect for velocity gain intercept (p=.003) with the low-order condition allowing subjects to track at a higher gain. The control-order x integrality interaction was significant (p=.016) but the integrality effect was not (p=.460). The interaction effect indicates that the separated condition showed higher gain than the integrated condition for the high-order of control group but the effect was reversed with low-order control. The interaction is illustrated in Figure 17. The emphasis effect was strong for velocity gain intercept (p<.0001) and in the expected order. The means were 11.139 dB for primary-emphasis (velocity), 7.788 dB for equal-emphasis, and 6.537 dB for secondary-emphasis. The primary-emphasis mean was significantly larger ($p<.01$) than the other two which did not differ.

INTEGRATED LOW-ORDER VELOCITY

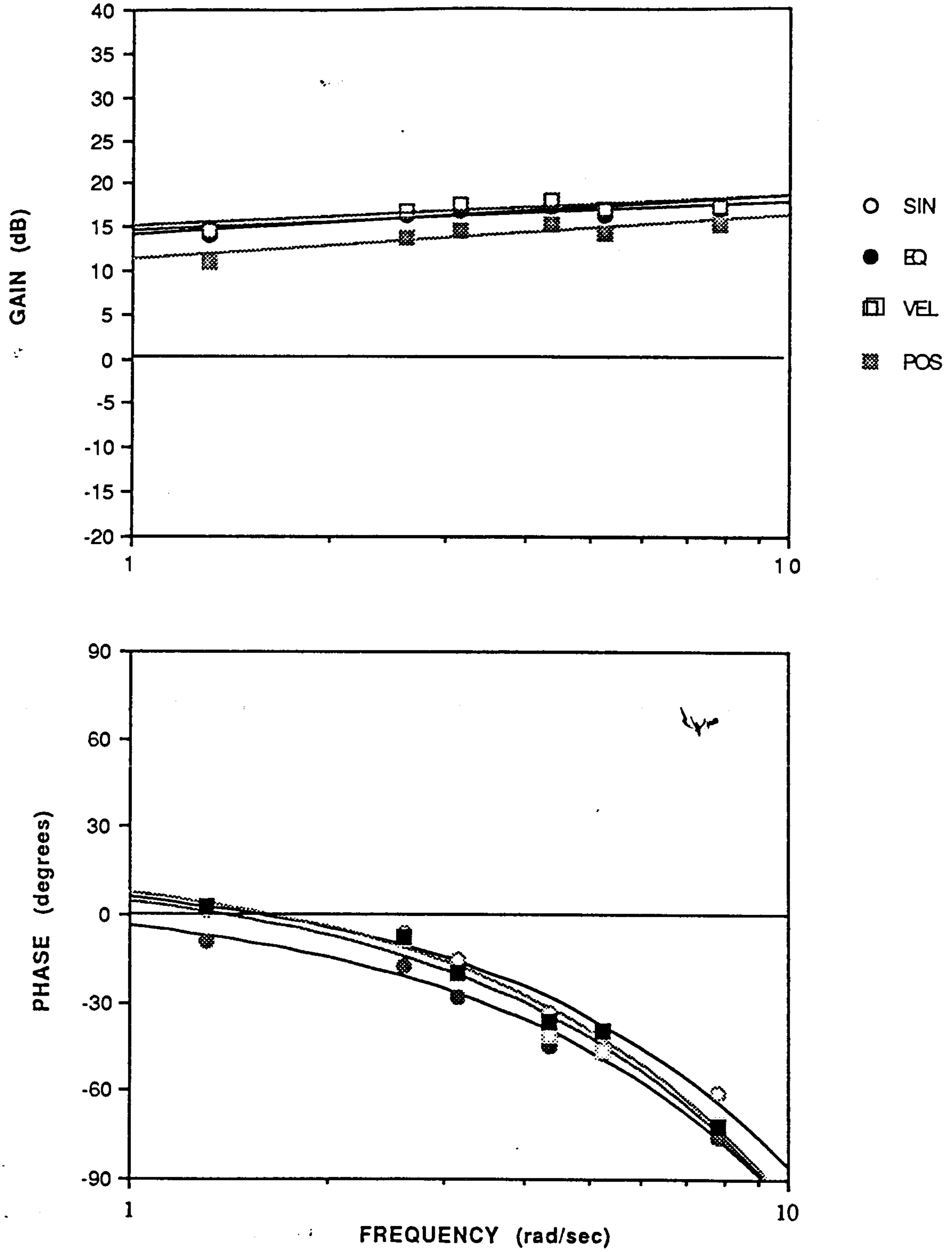


Figure 13- Bode Plot of Single and Dual-Axis Data for Low-Order Integrated Condition with Velocity Control Dynamics.

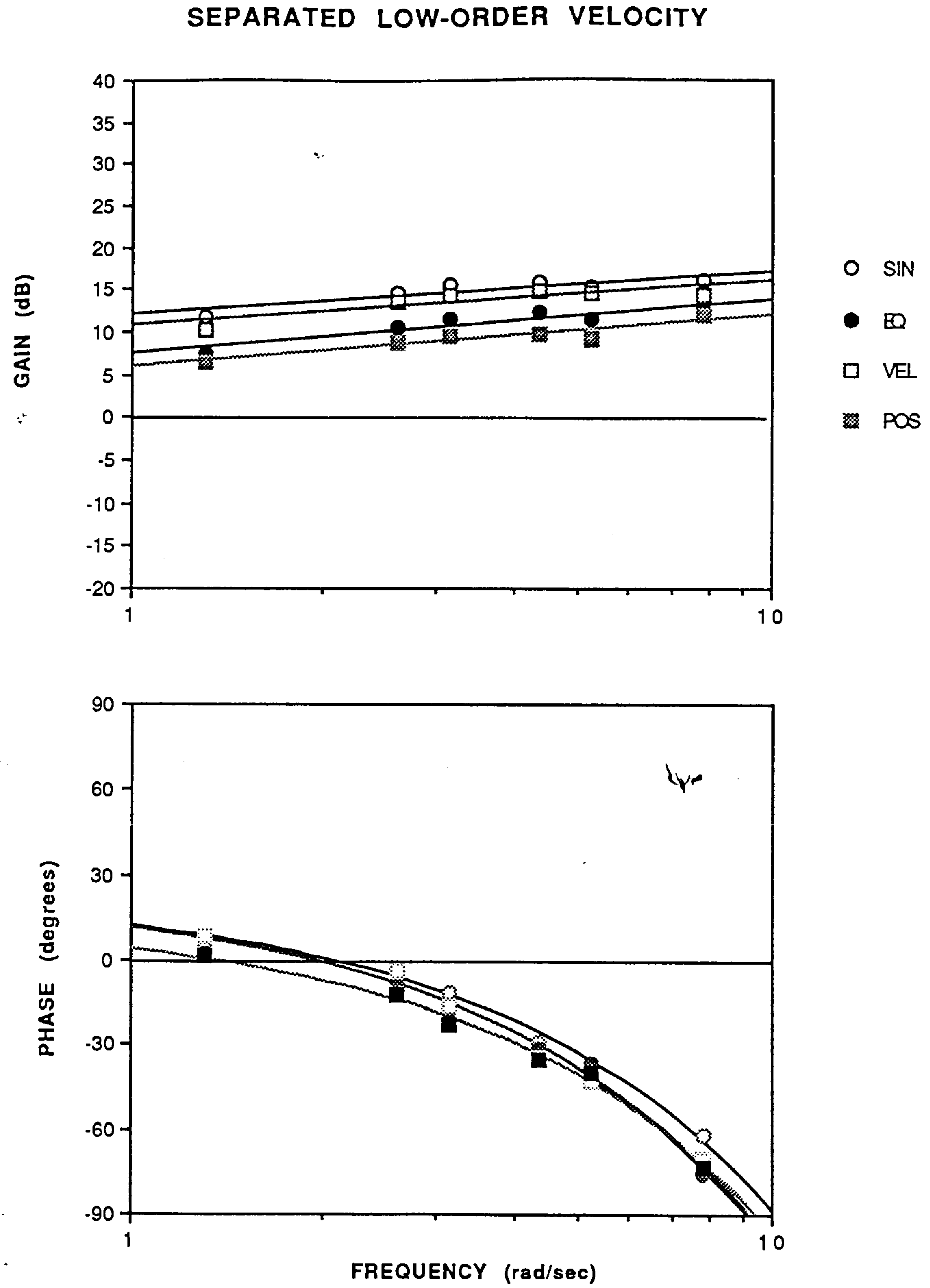


Figure 14- Bode Plot of Single and Dual-Axis Data for Low-Order Separated Condition with Velocity Control Dynamics.

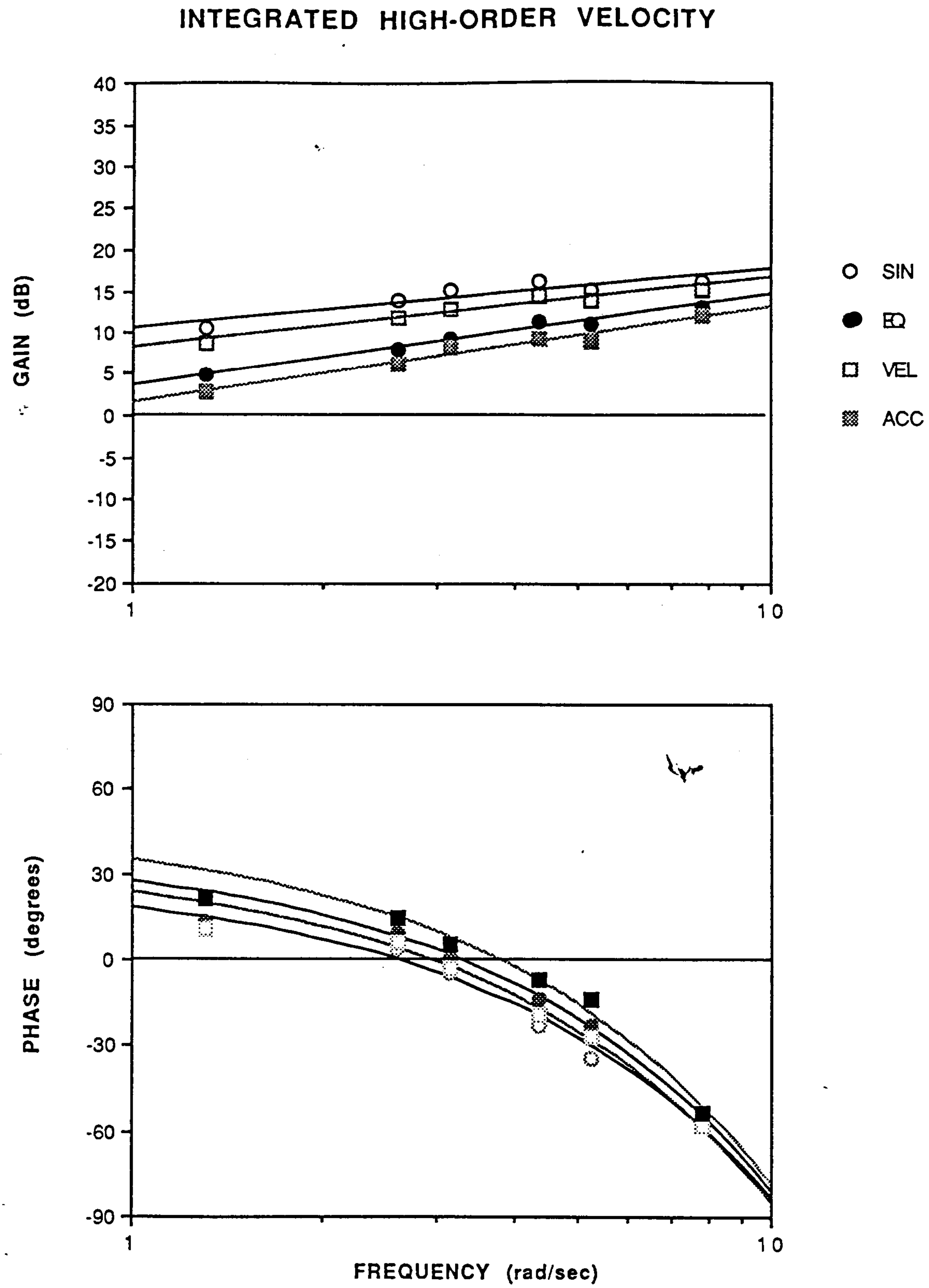


Figure 15- Bode Plot of Single and Dual-Axis Data for High-Order Integrated Condition with Velocity Control Dynamics.

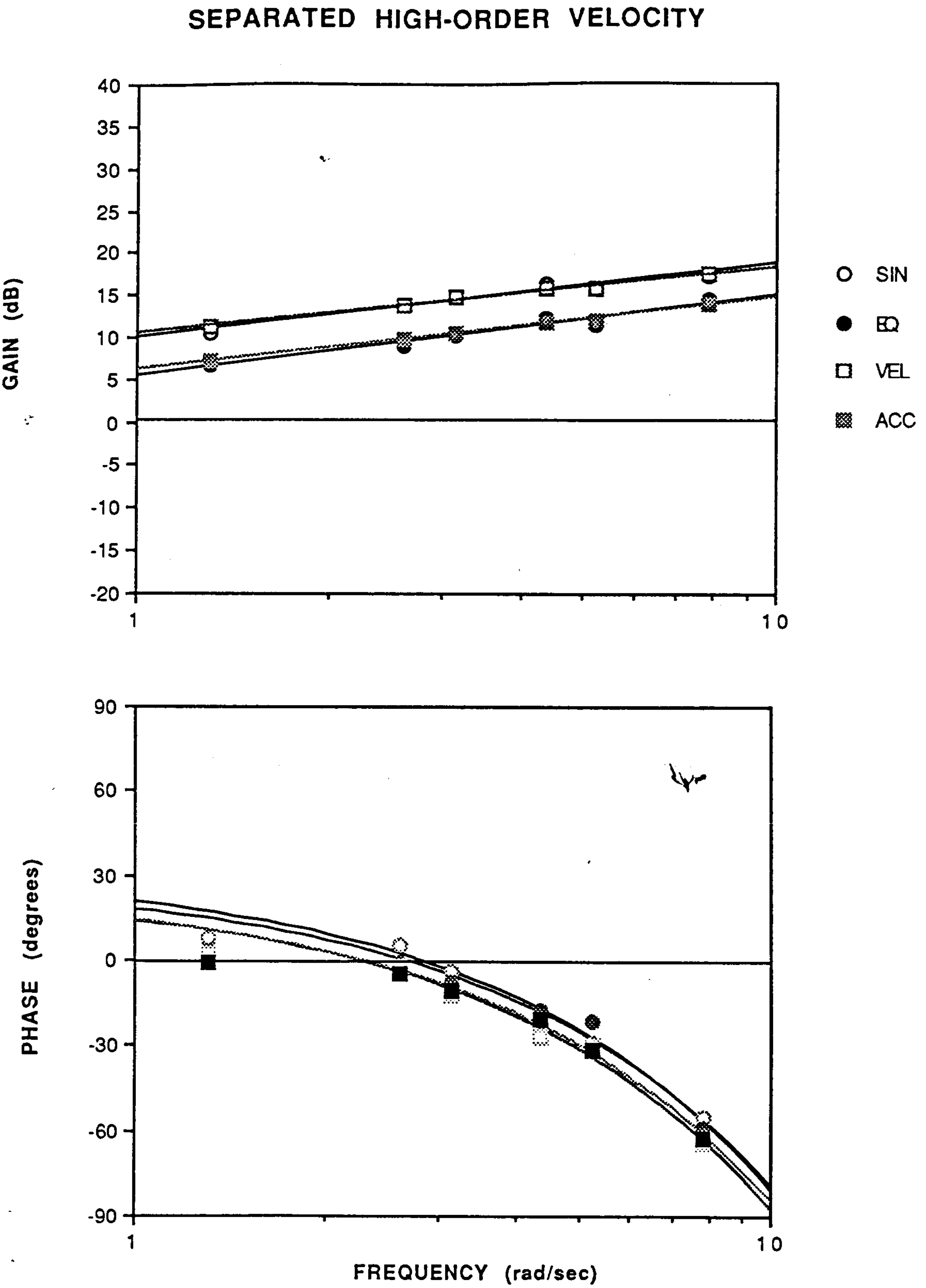


Figure 16- Bode Plot of Single and Dual-Axis Data for High-Order Separated Condition with Velocity Control Dynamics.

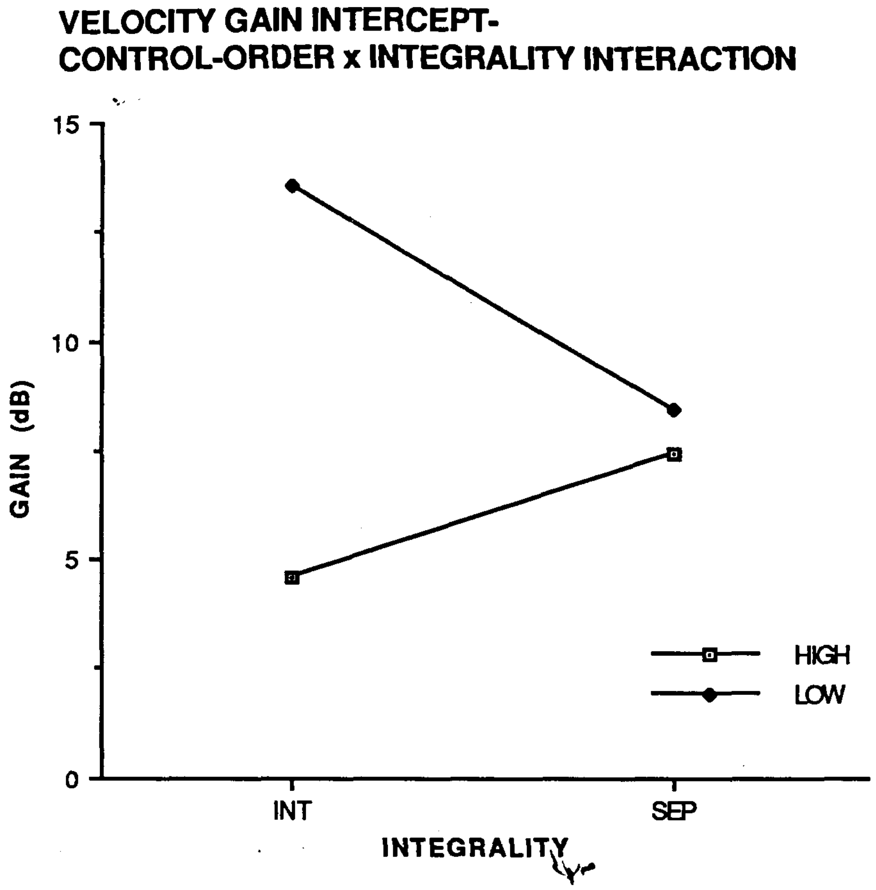


Figure 17- Control-Order x Integrality Interaction for Velocity Dual-axis Gain Intercept.

The position data Bode plots are shown in Figures 18 & 19. The emphasis effect was again strong (p<.0001) while no other effects approached significance for gain intercept. The emphasis means all differed from each other (p<.05) in the expected order. The means were 10.338, 4.887, and 2.881 dB for the primary, equal, and secondary emphasis intercepts respectively. Bode plots for the acceleration data are shown in Figures 20 & 21. Again, the emphasis main effect was the only significant result (p=.021). The primary mean was significantly higher than the other two means which did not differ. The mean primary, equal, and secondary emphasis gain intercepts were 21.995, 19.877, and 19.228 dB respectively.

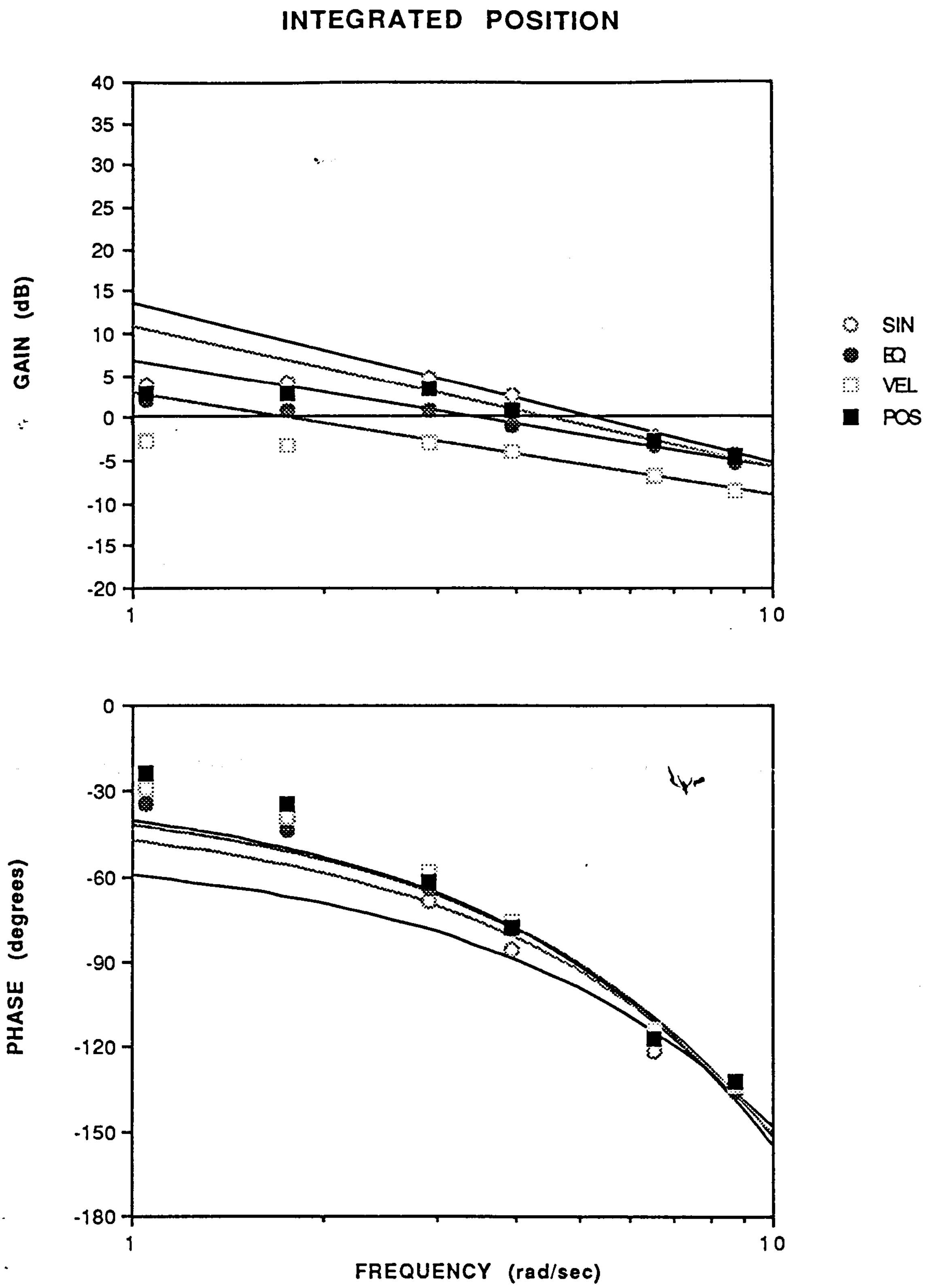


Figure 18- Bode Plot of Single and Dual-Axis Data for Low-Order Integrated Condition with Position Control Dynamics.

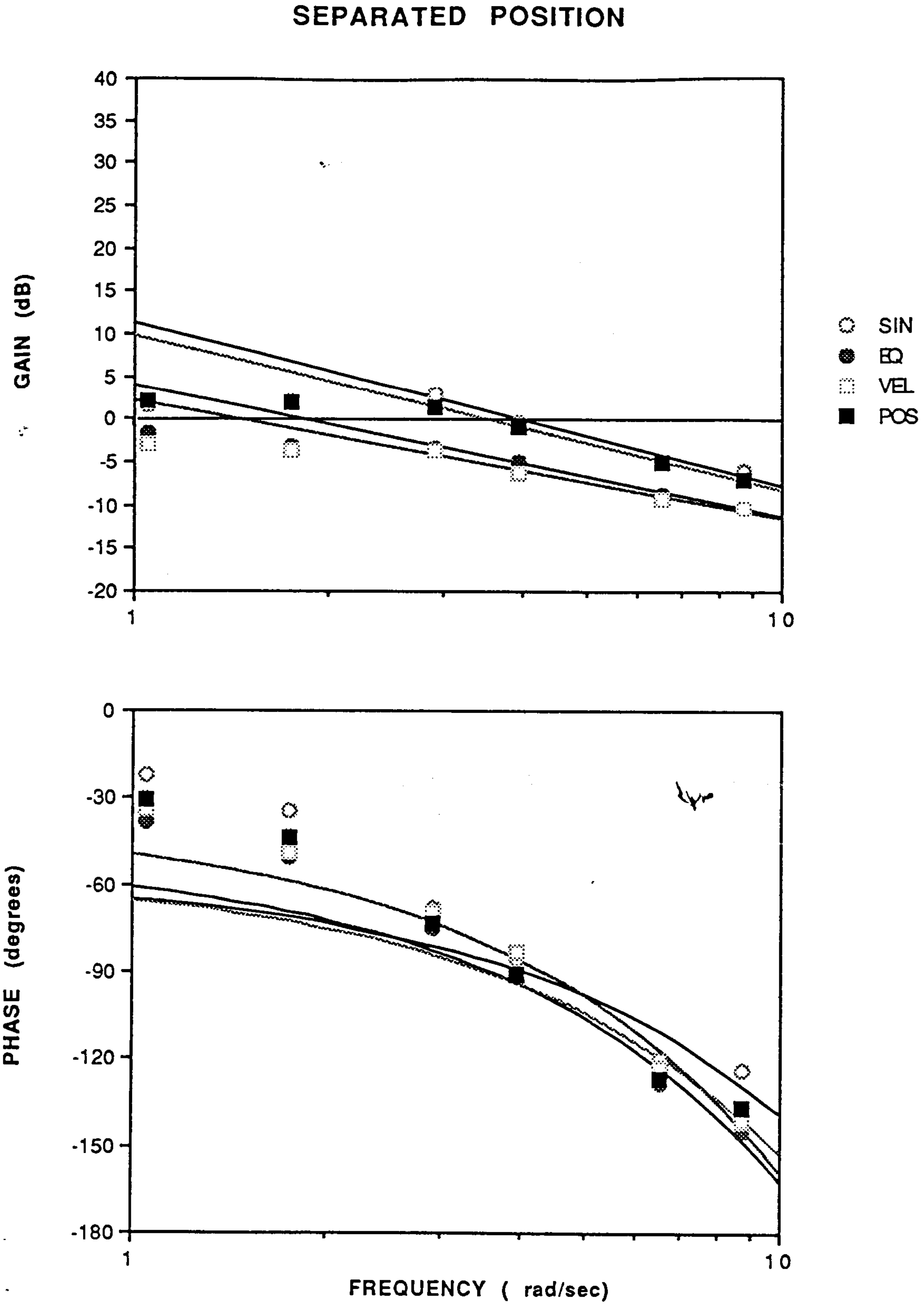


Figure 19- Bode Plot of Single and Dual-Axis Data for Low-Order Separated Condition with Position Control Dynamics.

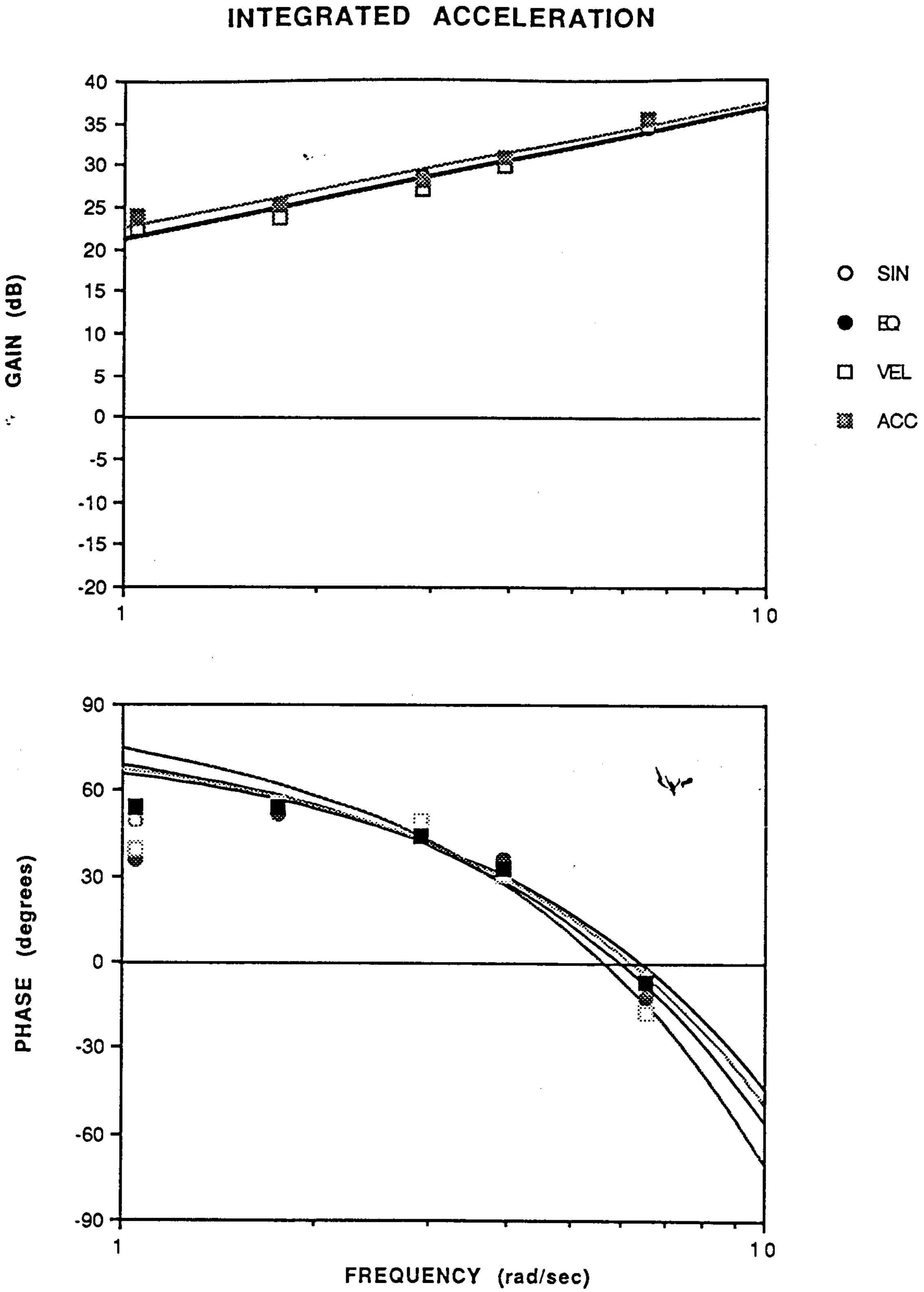


Figure 20- Bode Plot of Single and Dual-Axis Data for High-Order Integrated Condition with Acceleration Control Dynamics.

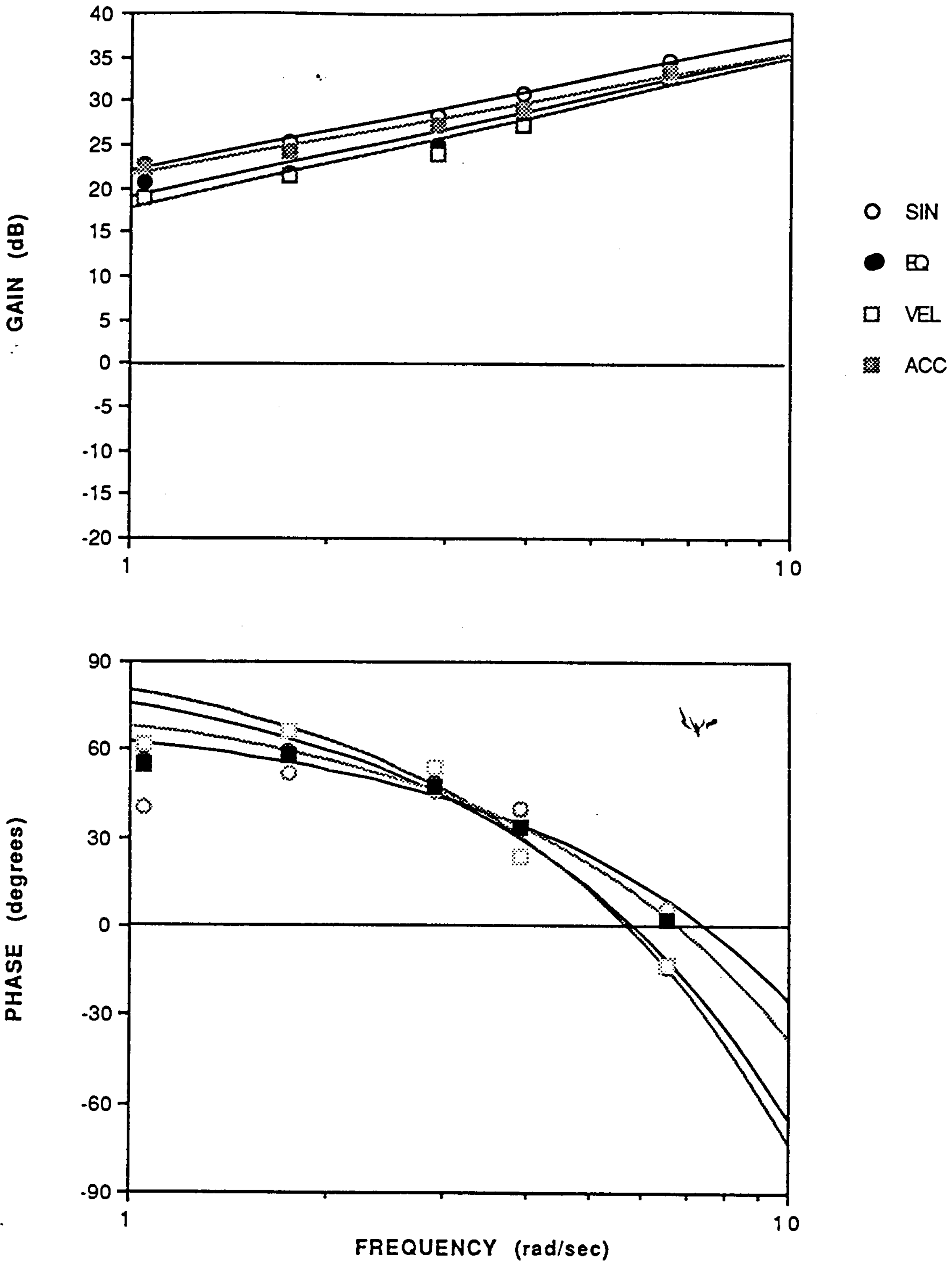

SEPARATED ACCELERATION

Figure 21- Bode Plot of Single and Dual-Axis Data for High-Order Separated Condition with Acceleration Control Dynamics.

iv) Gain Slope

There was a significant control-order effect for velocity gain slope (p=.0001). Gain slope was steeper for the high-order groups. There was no integrality main effect or control-order x integrality interaction. The emphasis main effect did not reach significance (p=.066) but the emphasis x integrality interaction did (p=.011) and is shown in Figures 22a & b. (The interaction is separated for each control-order condition so that the emphasis conditions may be identified).

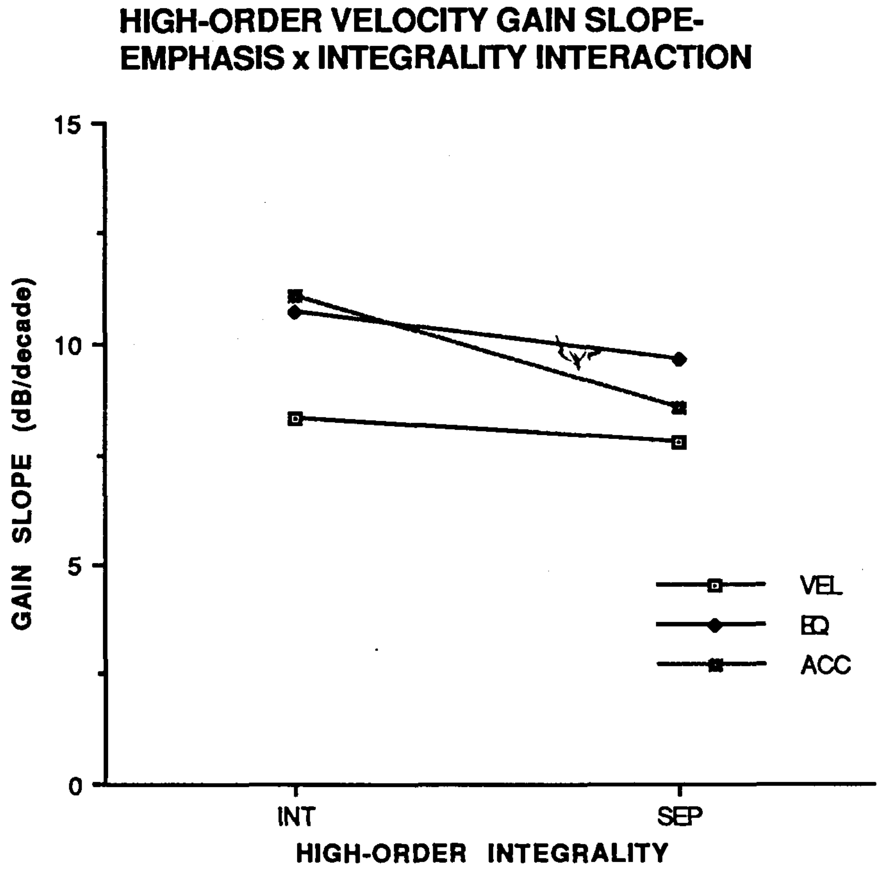


Figure 22 a- Emphasis x Integrality Interaction for (High-Order) Dual-axis Velocity Gain Slope.

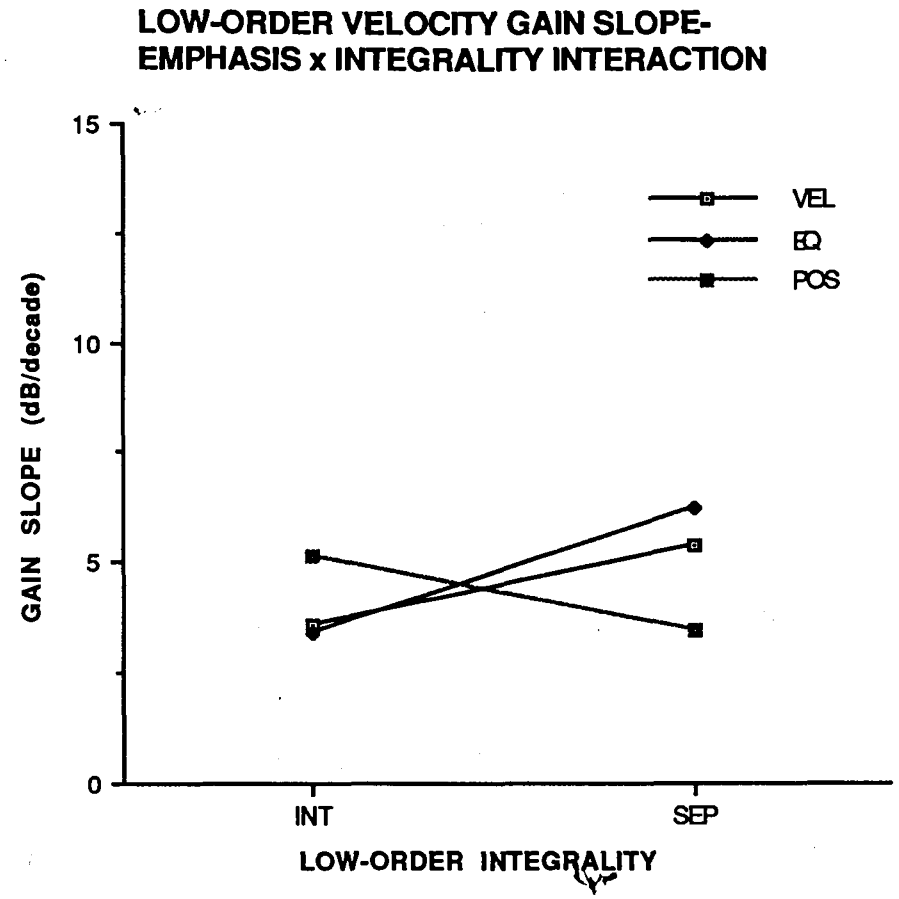


Figure 22b- Emphasis x Integrality Interaction for (Low-Order) Dual-axis Velocity Gain Slope.

The only main effect for position gain slope was of emphasis ($p<.0001$) with the position-emphasis gain slope significantly steeper ($p<.01$) than the equal and velocity-emphasis slopes which did not differ. The mean gain slopes were -17.336, -13.693, and -12.959 dB/decade respectively.

There were no acceleration gain slope effects that approached significance.

v) Phase Intercept

The velocity phase intercept data showed a significant control-order effect (p=.001) with the high-order conditions having a higher intercept than the low-order conditions. No integrality effect was evident (p=.762). There was a significant control-order x integrality interaction (p=.003). This effect is illustrated in Figure 23. The Tukey HSD test showed that the two integrated means differed significantly (p<.05) while no other significant differences existed. There was no main effect for emphasis (p=.619) but the emphasis x integrality interaction was strong (p=.0002) and is shown in Figure 24.

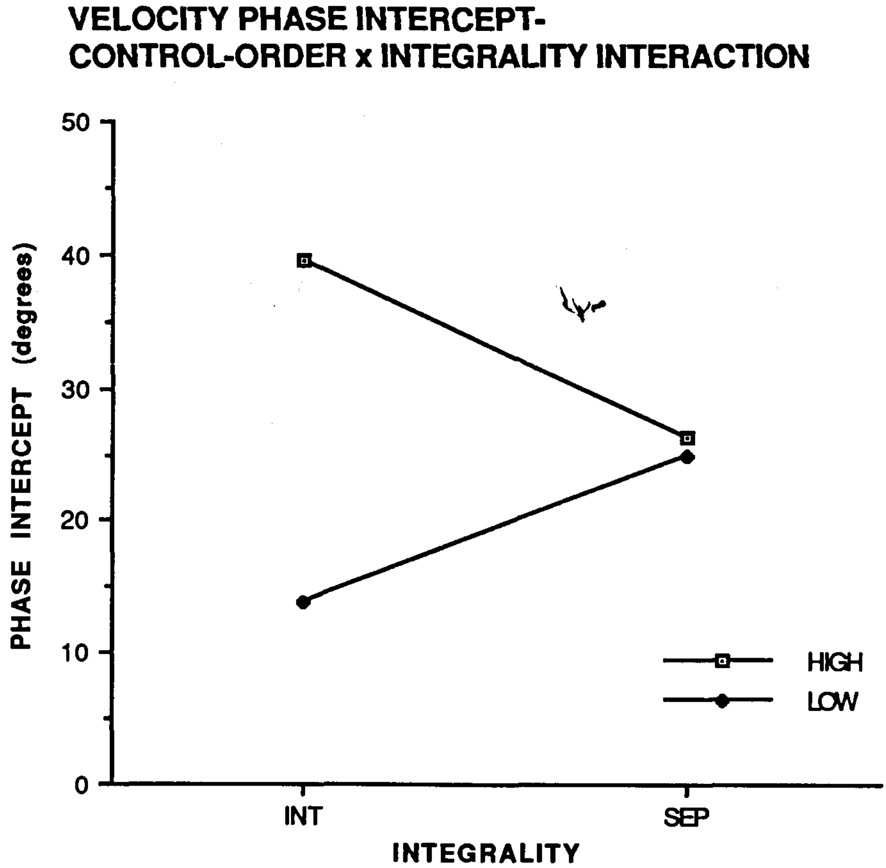


Figure 23- Control-Order x Integrality Interaction for Dual-axis Velocity Phase Intercept.

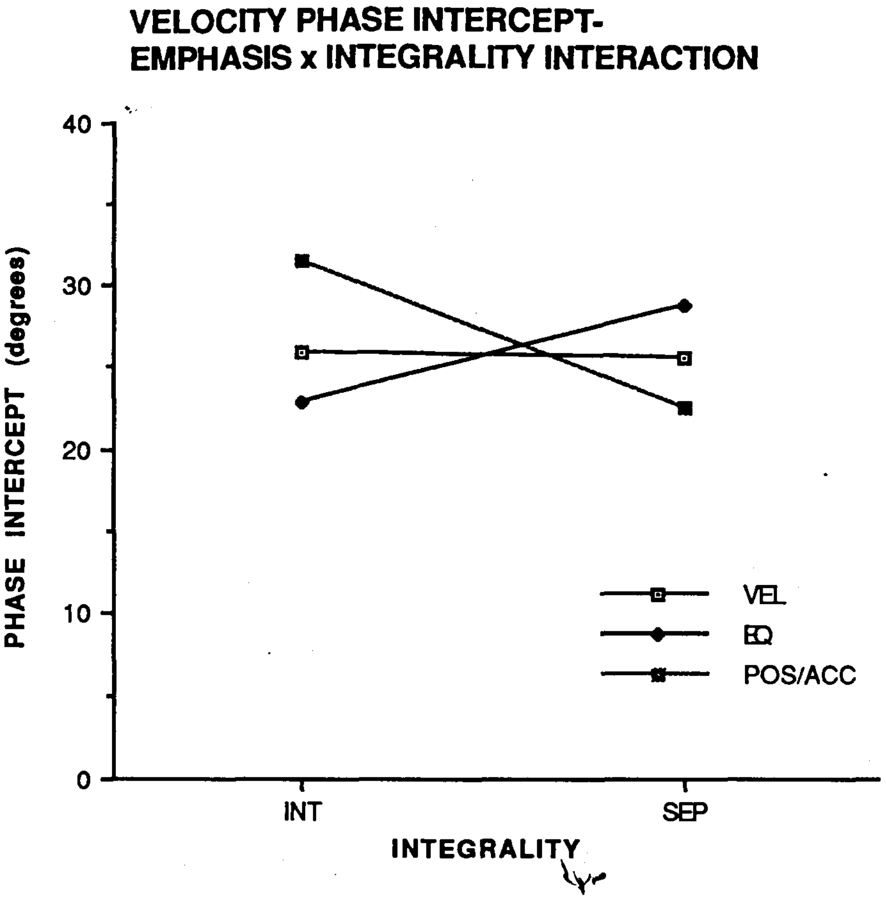


Figure 24- Emphasis x Integrality Interaction for Dual-axis Velocity Phase Intercept.

There were no significant effects for position phase intercept. The only significant effect for acceleration phase intercept was that of emphasis (p=.004). The means were 80.2, 86.6, 93.9 degrees for the acceleration, equal, and velocity-emphasis conditions respectively, and all differences were significant (p<.05).

The velocity phase intercept decrement data revealed a control-order x integrality interaction (p=.034) although the control-order main effect was not (p=.528) replicated. This interaction is shown in Figure 25. Pairwise comparisons revealed no significant differences between the means. The integrality main effect was nearly significant for the acceleration phase intercept decrement data (p=.050) with the separated conditions showing larger decrements as illustrated in Figure 26.

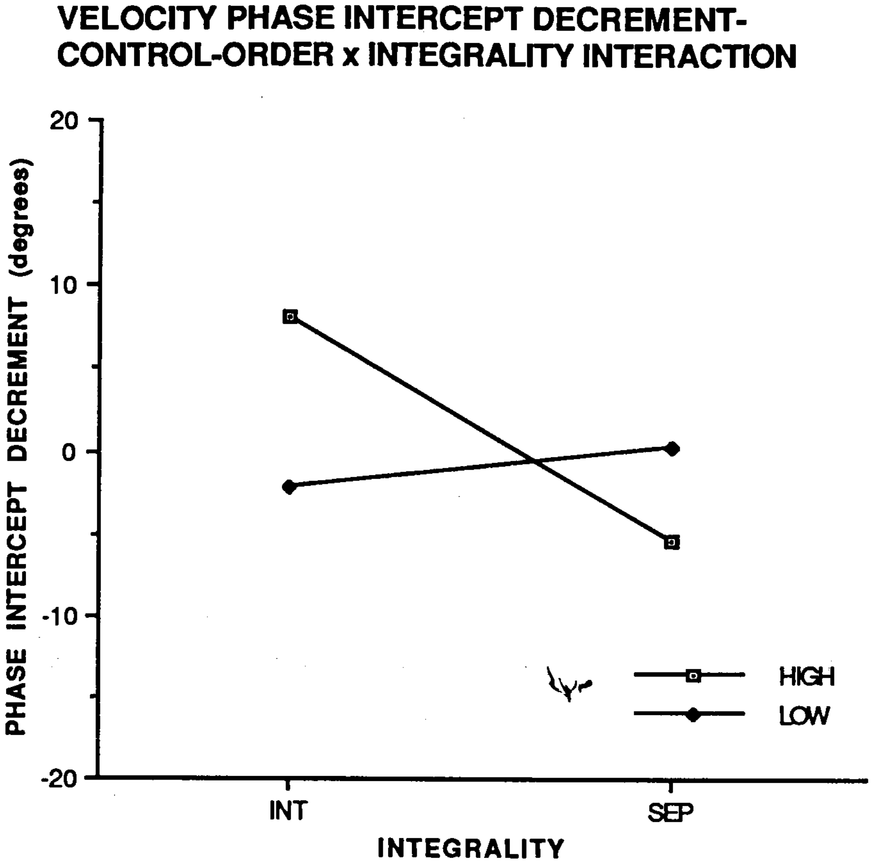


Figure 25- Phase Intercept Decrement- Control-Order x Integrality Interaction for Velocity Data.

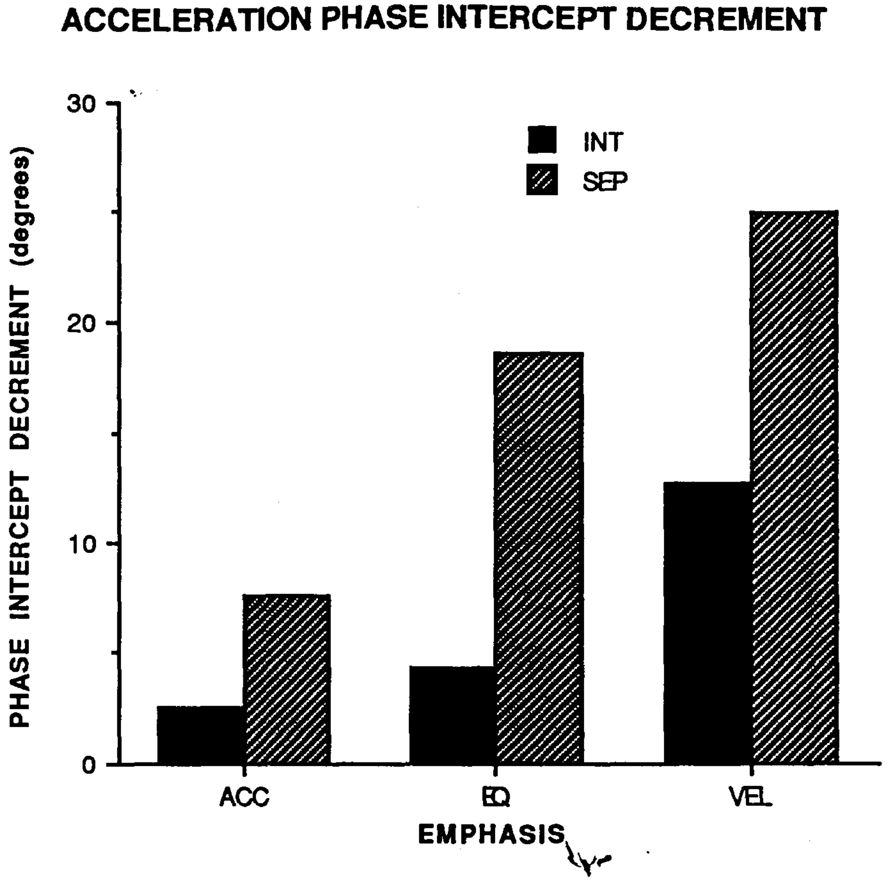


Figure 26- Phase Intercept Decrement- Emphasis Main Effect for Acceleration Data. (Integrality main effect approached significance [p=.050]).

vi) Phase Slope

The velocity phase slope data did not produce any significant effects although the emphasis x control-order x integrality interaction did approach significance (p=.052). The emphasis main effect was not significant for the position phase slope data (p=.067), but did reach significance for the acceleration phase slope data (p=.007). Tukey's comparisons revealed that the secondary and equal-emphasis means did not differ from each other but were significantly steeper than the primary-emphasis mean (p<.05). That is, effective time-delay (τ_e) was shortest when the higher effort was on the acceleration axis. This effect is illustrated in Figure 27. No other effects were found with the raw dual-axis phase slope data.

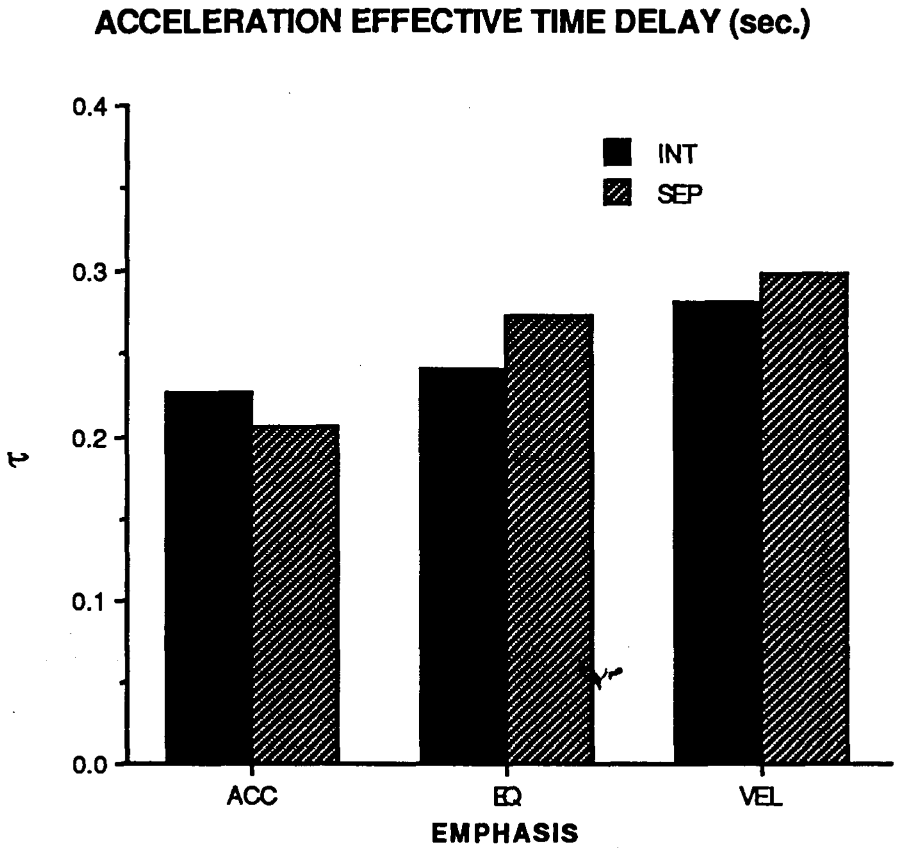


Figure 27- Emphasis Main Effect for Acceleration Phase Slope (τ_e).

The phase slope decrement scores did not reveal any significant effects other than the effects of emphasis present in the raw data analysis.

vii) Response Hold

A significant control-order effect was found for velocity response hold data (p=.041) with the high-order conditions exhibiting more response holds than the low-order condition. This effect is shown in Figure 28. (Response hold measures are expressed as the number of zero samples from the joystick per trial). The control-order x integrality interaction reached significance (p=.020) and this effect is illustrated in Figure 29. The emphasis effect was again strong (p<.0001) and in the expected order with the velocity-emphasis mean significantly lower (p<.05) than the other two means which did not differ. The emphasis x control-order interaction was present (p=.024) and is shown in Figure 30. Tukey's HSD test indicated that the identical effect for emphasis was replicated for the high-order conditions (p<.01) but not the low-order condition. Across control-order, the secondary and equal-emphasis means differed (p<.01) but the velocity-emphasis means did not.

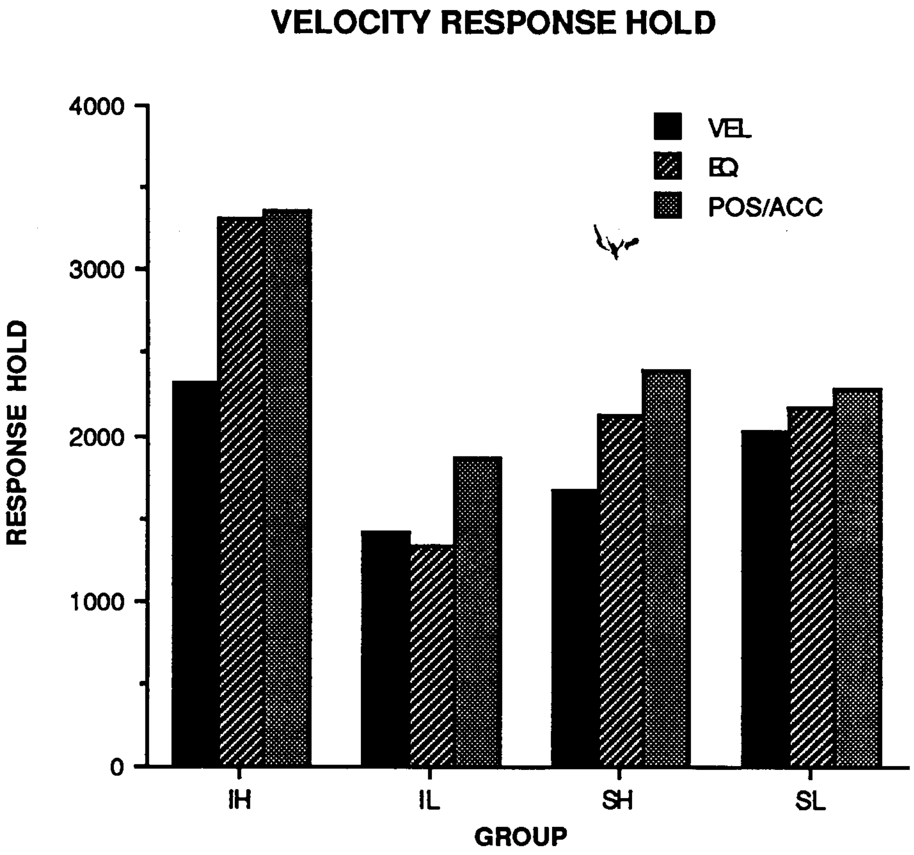


Figure 28- Control-Order and Emphasis Main Effects for Dual-Axis Velocity Response Hold.

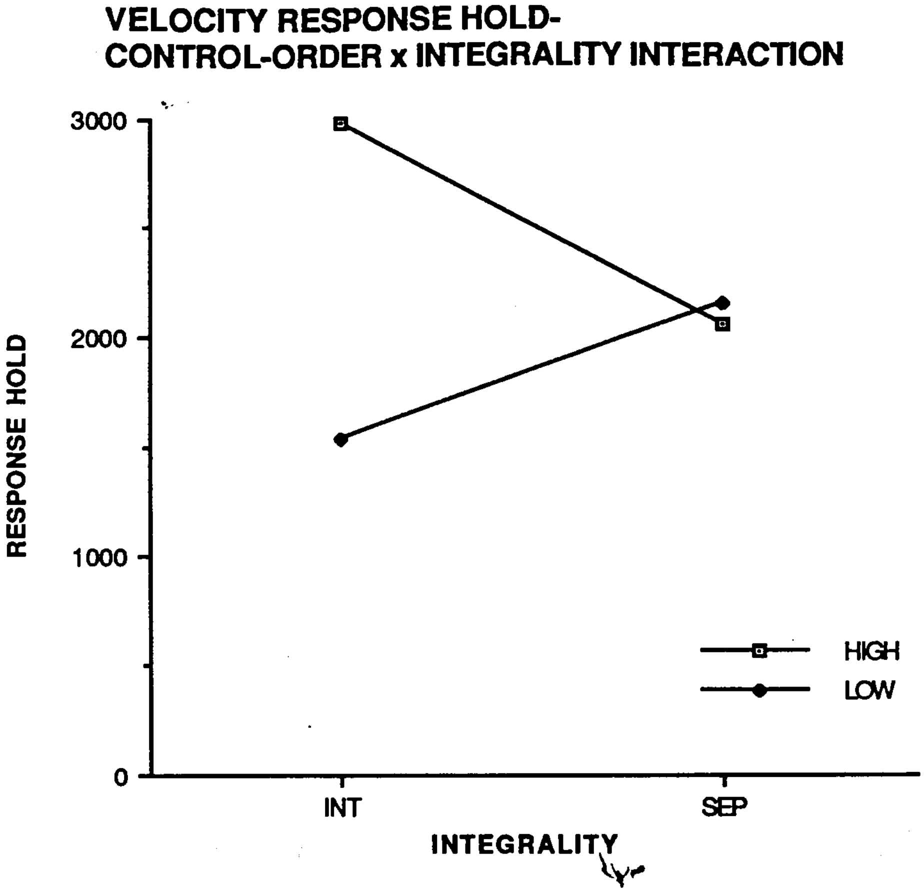


Figure 29- Control-Order x Integrality Interaction for Dual-Axis Velocity Response Hold.

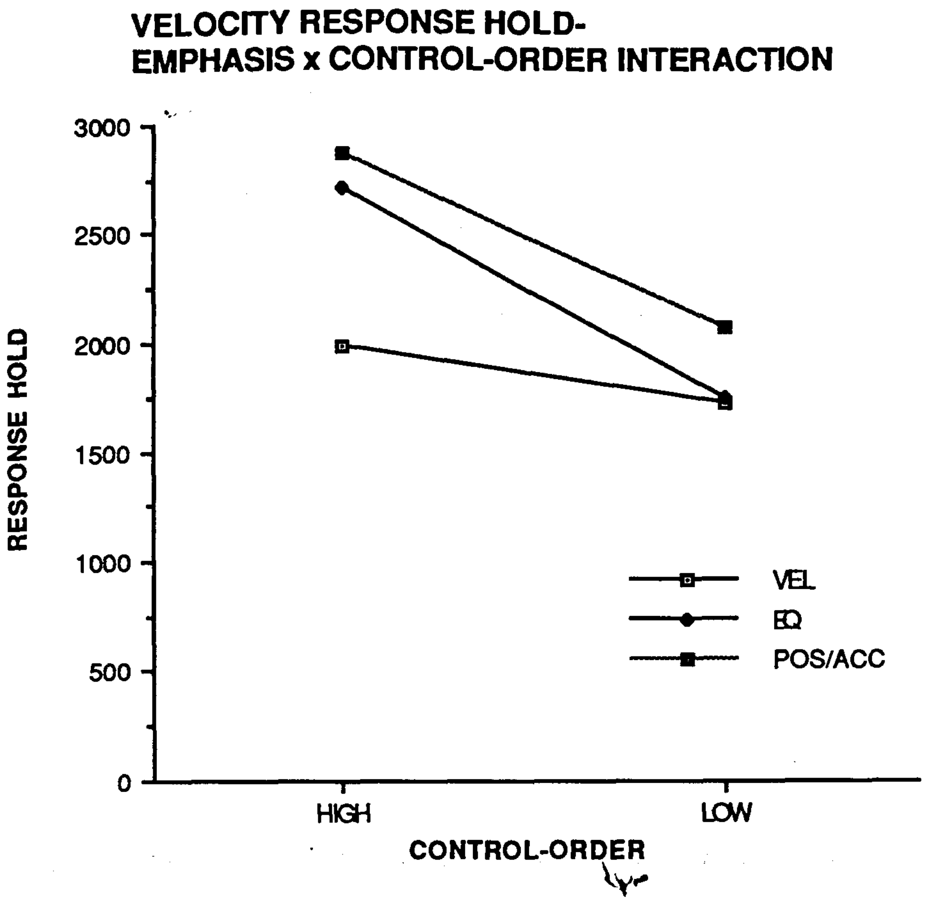


Figure 30- Emphasis x Control-Order Interaction for Dual-Axis Velocity Response Hold.

The emphasis main effect was strong for the position response hold data (p<.001) and the emphasis x integrality interaction was also present (p=.003). The emphasis means were in the expected order and significantly different (p<.05). These effects are illustrated in Figure 31. Across integrality, only the secondary (velocity) means differed (p<.01). For emphasis, the velocity mean was significantly higher (p<.01) than the other two means for the integrated condition, whereas in the separated condition, the position mean was significantly lower (p<.05) than the equal-emphasis mean which did not differ from the velocity-emphasis mean.

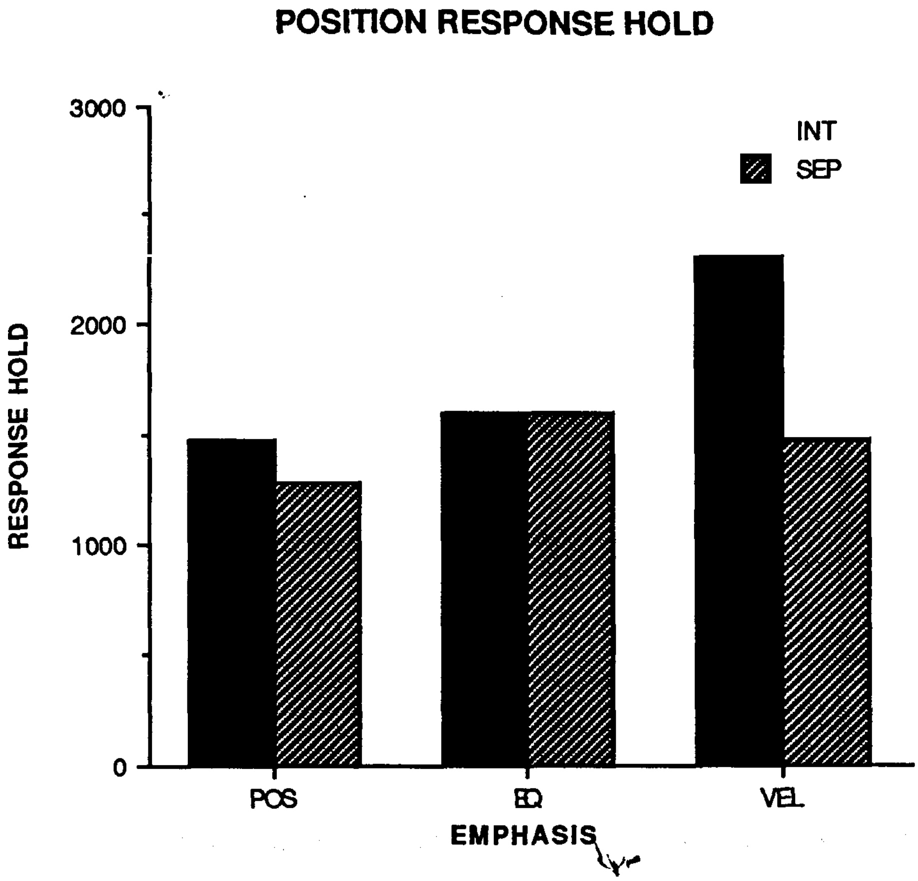


Figure 31- Emphasis Main Effect for Dual-Axis Position Response Hold.

The emphasis main effect approached significance (p=.064) for the acceleration response hold data and was in the expected order. No other effects approached significance.

No control-order or integrality effects reached significance for the response hold decrement data.

B. Mental Workload Data

The weighted workload means from each control-order x integrality group are shown in Figure 32. The weighted workload rating means indicated that the effect of integrality was evident whereas the effect of control-order was not. It was decided to pool the data over control-order so that a Kruskal-Wallis One-Way Analysis of Variance by Ranks could be performed to determine if the integrality effect was significant. The Kruskal-Wallis approach was chosen to analyze the Task Load Index ordinal data, although standard analysis of variance procedures have been used with conservative adjustments by other researchers (Hancock, 1989). The Kruskal-Wallis test seemed prudent in this case since only one measure of subjective data was collected from the subjects. Again, the mental workload data were collected immediately after the equal-emphasis dual-axis trials were complete and should be interpreted in this context only.

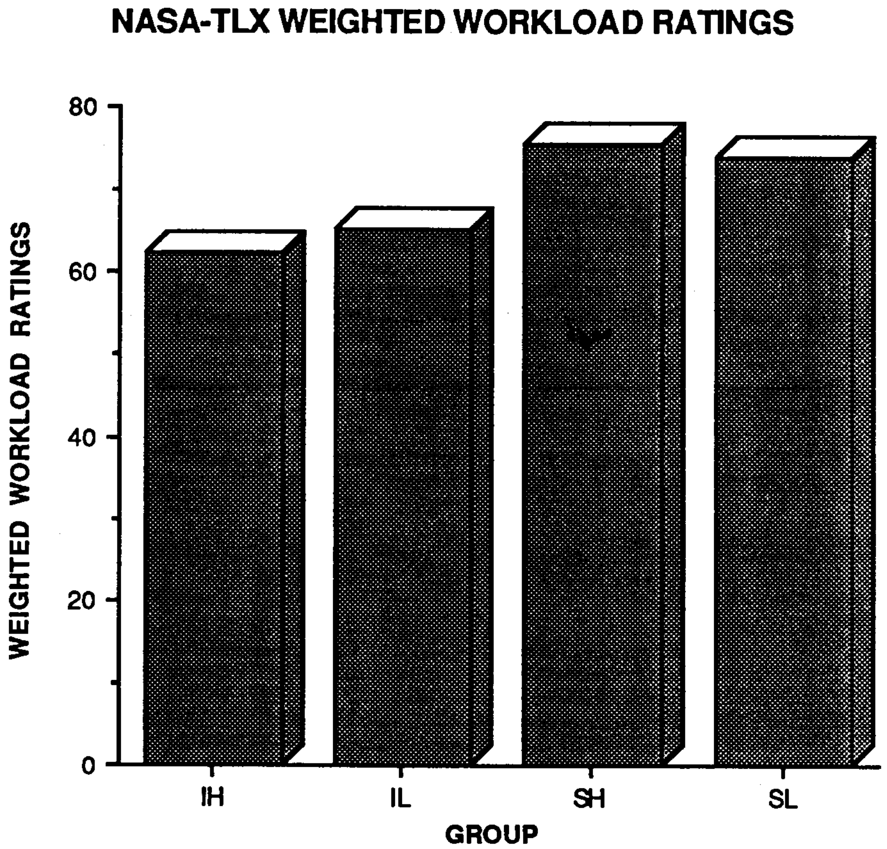


Figure 32- NASA-TLX Weighted Workload Ratings (Integrality Main Effect).

The effect of integrality was significant ($p<.05$) for the weighted workload scores indicating that subjects in the separated condition perceived a higher workload than the integrated condition subjects. The raw workload ratings shown in Figure 33 were examined to determine which, if any, of the subscales demonstrated the integrality effect. The mental demand ratings exhibited a significant integrality effect ($p<.05$) while none of the other subscales showed significant effects. The raw workload weights are shown in Figure 34 and comparisons between subscales revealed no significant differences.

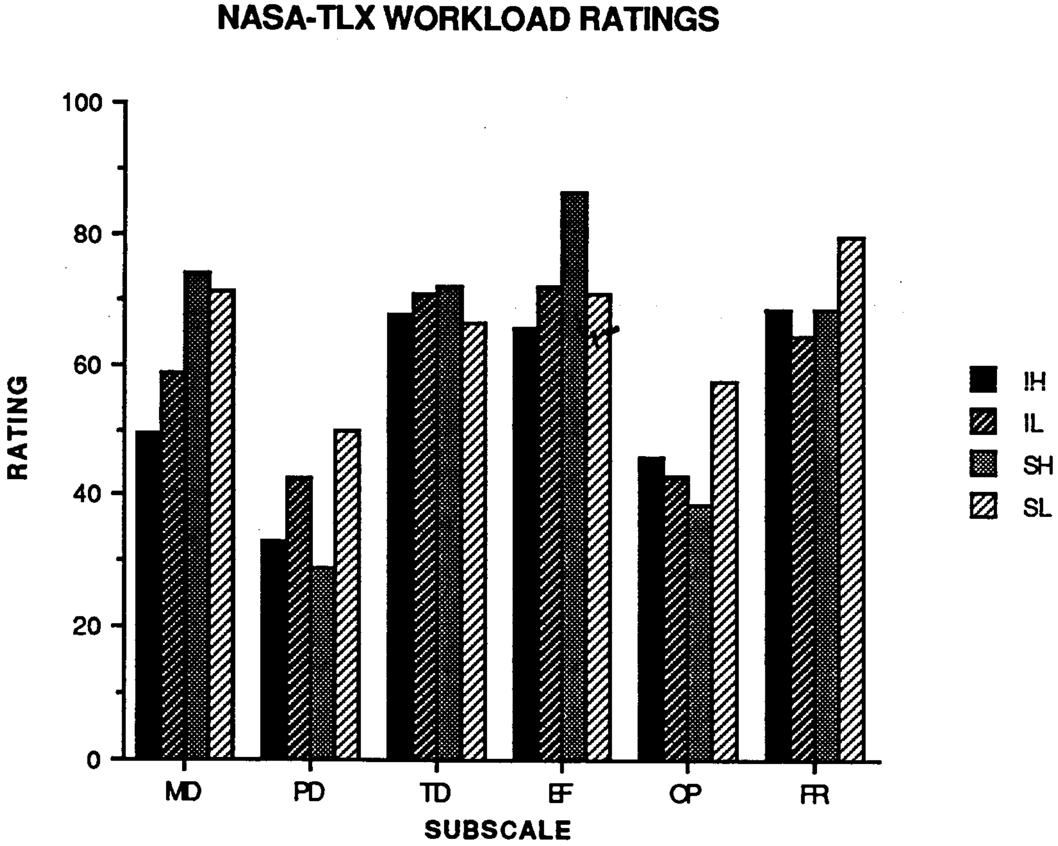


Figure 33- NASA-TLX Raw Workload Ratings (Integrality Main Effect for Mental Demand).

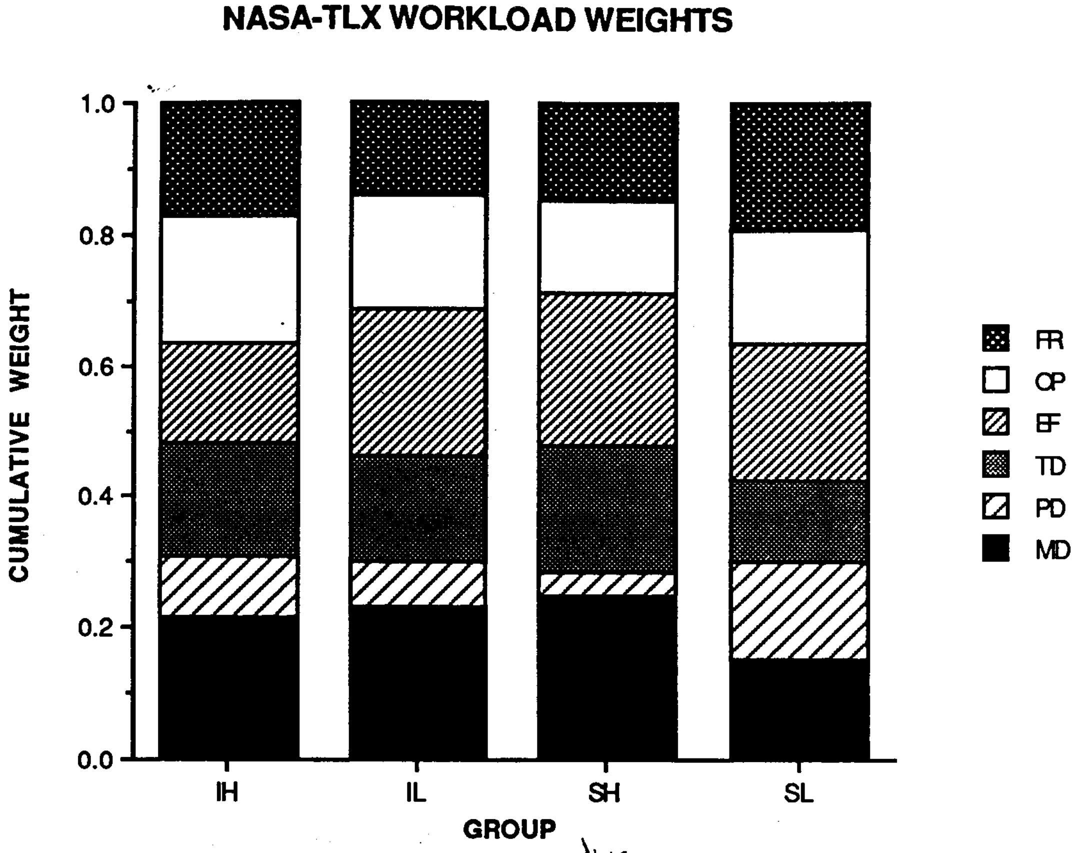


Figure 34- NASA-TLX Cumulative Raw Workload Weights.

VII. Discussion

The results for the tracking data are examined with respect to the integrality and control-order hypotheses. The task emphasis hypothesis is discussed throughout. The mental workload data are discussed separately.

A. Display-Control Integrality

It was hypothesized that integrated and separated conditions would differ in performance, and the separated conditions would show a performance advantage. Dual-axis and RMSE decrement results indicate quite clearly that better performance is achieved with integrated displays and controls. Results from the three dynamic conditions indicated a significant integrality effect with a time-sharing efficiency advantage clearly identified for the integrated condition. These findings do not support the compatibility of proximity hypothesis since integrated displays and controls were identified with better performance than separated displays and controls when combined with heterogeneous tasks. Also, confusion theory predictions were not supported as cross-talk was expected to be greatest for the integrated configuration, thus leading to poorer performance. The multiple resource theory which suggests that more resources are available with two-handed control was not supported and further significant performance trade-off differences were not realized for integrality. If resource availability were larger for the separated conditions then larger performance trade-offs would have been measured for the integrated conditions where fewer resources were expected. This effect cannot be explained by arguing that the tasks were data-limited as the effect of emphasis manipulation was significant for all control dynamics. It could be argued that separated displays are perceptually demanding. The resources demanded by the load of peripheral and foveal vision could be said to trade-off with the extra resources afforded with two-handed control. Further, since this cost for the separated conditions is imposed at the perceptual stage, it could be argued that the information transmitted along the channel is of poorer quality than that for the integrated conditions.

B. Control-Order and Integrality

Several parameters were measured in order to provide support and explanatory power for the RMSE performance results. However, not all other variables identified an integrated advantage. The control speed data indicated that the separated conditions responded with higher control speeds for the velocity and acceleration axes. Higher control speeds are evidence for greater resource allocation and this finding supports the multiple resource account that more resources are utilized with two-handed control. The effect for integrality was largest with high-order of control (where more demand is imposed). The control speed data were not data-limited as they were affected by emphasis manipulations for all control dynamics, integrality, and control-order conditions.

The gain intercepts served as an overall index of gain and indicated that subjects controlled the velocity axis with a higher gain in the low-order conditions than in the high-order conditions. This effect is not surprising as it shows that there are fewer resources available to control the velocity axis when combined with acceleration dynamics than when combined with position dynamics. This resource or capacity effect is expected, by definition, from the task difficulty manipulation. Dual-axis gain intercept was significantly lower for the low-order velocity conditions when compared to the high-order velocity intercepts. The control-order x integrality interaction can be interpreted in the same manner as the control speed interaction. A separated gain advantage was noted with the high-order velocity data but not with the low-order data. In fact ,the low-order integrated gain was higher than that of the separated condition. This paradox is interesting to note. The separated high-order advantage seems to indicate a greater resource availability while the integrated low-order advantage is similar to the findings of Levison & Elkind (1967) in their examination of control theory parameters and peripheral and foveal strategies with separated displays. It appears that the additional resource availability (advantage) of the separate hand control (high-order) trades off with the perceptual resource demand (disadvantage) of the separated displays (low-order). These interpretations must be weighed in consideration of non-significant differences between means. Emphasis manipulation affected the gain of all control dynamic conditions indicating that subjects are able to trade-off the amount of control they can provide between the two tracking axes.

Gain slope analysis also revealed a control-order effect for velocity data with steeper slopes resulting for the high-order conditions. Because the acceleration axis was the most difficult, the gain slope of the easier velocity axis is biased toward that of the more difficult axis. That is, acceleration control strategies interfered with the control of the velocity axis, as acceleration gain slopes were about 10-20 dB/decade steeper than the velocity slopes. This result replicates similar findings noted by Fracker & Wickens (1989) and Levison & Elkind (1967) in dual-axis tracking, and also Kelso et. al. (1979) in two-handed movements, and serves to further document the effect of confusions. Further, gain slope was least affected when acceleration dynamics were controlled, as evidenced by a non-significant emphasis main effect. That is, the effect of combining velocity tracking with acceleration tracking has little effect over the gain slope of the acceleration axis even under severe priority manipulations. However, velocity gain slopes were affected by acceleration tracking, and position gain slopes were sensitive to emphasis manipulation. More difficult tasks contaminate easy tasks, but this effect was not reversed (for gain slope) under the priority manipulations used here.

The velocity gain slope emphasis x integrality interaction illustrated in Figures 22 a & b is difficult to interpret. It appears that the integrality conditions differ mostly when the non-velocity axis is emphasized although obvious explanations for these results do not seem possible. It is possible that the pooling of the position and acceleration control-orders led to this interaction which seems largely based on one-third of the subjects' control effort.

The control-order effect was again evident for the velocity phase intercept data in much the same manner as was detected for the gain slope data. The high-order velocity conditions indicated a higher phase intercept and this provides further evidence of contamination by acceleration tracking, since the acceleration phase intercepts fell about 60-90 degrees above the velocity intercepts. The control-order x integrality interaction reached significance for both dual-axis data and decrement scores and is easiest to discuss with reference to the decrements as shown in Figure 25. The position phase intercept lies about 60-90 degrees below the velocity intercept. It would not be expected that the velocity (more difficult) axis would be greatly affected by the position tracking and this is reflected by near-zero decrements for both integrality conditions, although the integrated condition shows an insignificantly larger negative decrement (i.e., biased toward the position intercept). The velocity axis would be expected to be contaminated by the more difficult acceleration axis as discussed above, and this was noted by positive decrements for both integrality conditions. The integrated condition demonstrated the larger decrement toward the concurrent axis, although the difference between the means was non-significant. Again, confusions are evident.

The acceleration phase intercept decrement data demonstrated an integrality effect with the separated conditions showing the largest decrements, although the raw dual-axis intercepts did not exhibit the same effect. These decrements were not in the direction which would support a confusion or cross-talk explanation. Examination of the phase slope (effective time delay, τ_e) data seems to provide the most insight concerning this finding. It is suggested that the integrality effect for acceleration phase intercept is a residual effect of a longer effective time delay with the separated conditions. Effective time delay was affected under priority manipulations only with acceleration control dynamics. That is, trade-offs in terms of processing time were only evidenced in the most difficult (acceleration) axis, indicating high resource demand or scarcity of processing resources. It is suggested that the non-significantly larger acceleration phase slopes of the separated condition raised the phase intercepts of the separated condition to a significant level. That is, the acceleration phase intercept data may be an artifact of τ_e. No other explanation is obvious as to why the phase intercepts of acceleration tracking data would be raised when combined with velocity tracking.

Velocity response hold data revealed a significant control-order effect with more response holds in the high-order conditions. This finding suggests that there are fewer resources (or less capacity) available for the control of the velocity axis when the more difficult acceleration axis is also controlled. The control-order x integrality interaction was significant and again demonstrates what appears to be a trade-off between more available resources with separated controls and a greater perceptual resource demand from the separated displays. The effect of control-order was much larger for the integrated conditions than the separated conditions. Position response hold data were effected by priority manipulation as were velocity response hold data when combined with acceleration dynamics. Acceleration response holds were not significantly altered by priority manipulation. These findings reiterate the insensitivity of the more difficult tasks (axes) to contamination.

Lower-order control relieved the demands imposed on the subjects as evidenced in lower RMSE, higher control speeds, higher gain, and less confusion between the control of each axis. However, low-order of control did not help the separated conditions realize an advantage over the integrated conditions. Control speed, gain intercept, phase intercept and response hold data all seem to indicate that the high-order separated conditions had an advantage when compared to the same variables of the integrated condition, although this advantage is never realized at a performance (RMSE) level.

The effects of task emphasis were quite robust, with respect to the variables measured in this study. However, more stringent tests of performance trade-off quantification (measured for RMSE) did not reveal significant effects for control-order or integrality. As evidenced in the POC representation of Figure 8, the magnitude of trade-off was in the expected direction for control-order (i.e., the high-order velocity trade-offs were greater than those of the low-order groups), but not in the expected direction for integrality (separated conditions exhibited larger performance trade-offs). It did not seem prudent to continue this line of analysis with the other dependent variables since the RMSE data did not approach significance. It is suggested that greater differences in task difficulty are required in order to demonstrate performance trade-off differences.

C. Mental Workload

The mental workload data indicate that subjects in the separated conditions experienced a higher workload than subjects in the integrated conditions. The tasks in this experiment were assumed to be resource-limited as evidenced by performance trade-offs with priority manipulations. However, workload indices did not appear to be sensitive to the effects of control-order in this between-subject design. Yeh & Wickens (1988) stated that for resource-limited tasks, subjective measures are driven by the total amount of resources invested and dominated by the demands on working memory. It is argued that the separated displays load the perceptual system thereby imposing greater demands upon working memory and elevating the subjective measures. The workload data presented here cannot be conclusively interpreted as a resource effect, with the separated control conditions utilizing a greater amount of resources (with two-handed control). If greater resources were invested then a performance advantage would be expected from the separated condition which was in fact, the opposite of the findings presented here.

D. General Discussion

The separated advantage predicted by the independent hemisphere resource model of Friedman was not supported with improved performance, and in fact an integrated advantage existed for both levels of control-order (task difficulty). However, the control-order x integrality interactions for velocity control speed, gain intercept, phase intercept and response hold data suggest that more response-related resources may have been available for the separated conditions, but only utilized in the high-order condition. That is, analysis of these variables suggests that the high-order separated condition has an advantage over the high-order integrated condition but the integrality effect is reversed for the low-order conditions. The following explanation is offered. There appears to be a definite cost of separated displays in terms of loading peripheral vision and thus perceptual resources. This effect is well documented throughout the literature (eg., Levison & Elkind, 1967; Wickens & Liu, 1988). It should be noted however, that no formal or informal eye-movement measurements were taken and that explanations based on peripheral versus foveal strategies are speculative. In this experiment the perceptual load of separated displays should remain fairly constant across control-order since factors such as screen size and head position do not vary. Although it may be argued that the cursors were kept closer to the target in the low-order condition, any visual separation greater than 2 degrees is said to fall away from foveal vision (Wickens & Liu, 1988). High-order of control demands a greater amount of control effort and therefore, more response-related resources are utilized. However, in the low-order separated condition the additional resources afforded by two-handed control are not utilized to the extent that they overcome the (constant) cost imposed by separated displays. It is suggested that the easier control dynamics do not demand the total resource capacity in order to maintain control over the system. Therefore, the low-order integrated advantage is interpreted as a result of perceptual loading imposed on the separated condition. The high-order separated "advantage" is a result of additional response-related resources demanded by the difficult control dynamics. The term "advantage" in this last sentence is indicative of the dependent variables relevant to this discussion and not the performance (RMSE) variable.

This separated "advantage" is not evident at a performance (RMSE) level. In fact, the control-order hypotheses of this study suggested that if there were to be a separated advantage, it would occur in the low-order condition first. These predictions from existing literature and confusion theory were based on the premise that two-handed movements which are temporally incompatible may be subject to more contamination in a high-order or more difficult condition. The results presented here (gain slope, phase intercept) suggest that cross-talk is indeed quite evident between two-handed controls but is even greater between the tracking axes of a single-handed control when heterogeneous tasks are performed.

VIII. Conclusion

Integrated displays and controls yield better performance than separated displays and controls when heterogeneous tasks are performed. This is evidenced in spite of the fact that the integrated conditions were more susceptible to confusions or cross-talk between tracking axes. Also, there is evidence that the separated condition provides more response-related resources. However, these additional resources are not utilized to the extent that the subjects are able to overcome the temporal invariance imposed on two-handed movements at a performance level. It is well founded that separated controls should be paired with separated displays in order to provide compatible stimulus-response mappings. However, the evidence presented here does not support the compatibility of proximity hypothesis in matching the proximity of the central processing requirements of the two tasks with the S-R proximity. Evidence of time-consuming internal processing delays required for incompatible mapping operations in the integrated conditions were not evident as non-different effective time delay measures were found between the integrality conditions.

At what level then, does the separated system break down? It is suggested that separated displays impose a perceptual cost by requiring the operator to use peripheral vision to monitor at least one of the axes. This explanation does not seem able to account for potential separated advantages that were shown to exist at a response level, although it could be argued that the quality of data transmitted via the peripheral vision system is poorer than that of the foveal system, and that the variables studied here are insensitive to this degradation. Whatever the source of the degradation, the variables examined here were unable to describe the overall system performance.

Evidence for cross-talk between channels was evident in several measures and consistently demonstrated to be larger between axes for integrated conditions than between hands for separated conditions. Since it appears that integrated configurations are favorable for manual control tasks such as those described here, it would be advantageous to further the development of intelligent/adaptive machinery which is able to compensate for cross-talk between axes in multi-axis unilateral control systems.

Further research is suggested in the localization of the separated channel breakdown. It is suggested that this phenomenon is not entirely (if at all) response-related. Instead, it is suggested that separated displays impose greater perceptual demand on the operator, and are a potential limiter in the quality of information transmitted through the channel. Because it is important to incorporate S-R compatibility into systems such as the one studied here, it is suggested that further methods of separating displays at a perceptual level are examined without physically separating the visual stimuli. Research in this area may lead to a better examination of the resource capacity and allocation policies governing two-handed control.

Finally, the results presented here indicate that both resource and confusion theories can provide an account for the data although a more fine-grained analysis appears to be necessary in order to determine the breakdown of the separated system. Thus, further developments toward a tractable theory of divided attention would benefit from the inclusion of both resource and confusion considerations.

APPENDIX A- GLOSSARY OF ABBREVIATIONS

I	INTEGRALITY
INT	INTEGRATED
SEP	SEPARATED
C	CONTROL-ORDER
LOW	LOW-ORDER
HIGH	HIGH-ORDER
IH	INTEGRATED HIGH-ORDER
SH	SEPARATED HIGH-ORDER
IL	INTEGRATED LOW-ORDER
SL	SEPARATED LOW-ORDER
E	EMPHASIS
EQ	EQUAL-EMPHASIS
VEL	VELOCITY-EMPHASIS
POS	POSITION-EMPHASIS
ACC	ACCELERATION-EMPHASIS
SIN	SINGLE-AXIS
PRIMARY SUBJECTS'	DENOTES THE AXIS WHICH RECEIVES 75% OF THE EFFORT
SECONDARY SUBJECTS'	DENOTES THE AXIS WHICH RECEIVES 25% OF THE EFFORT
MD	MENTAL DEMAND
PD	PHYSICAL DEMAND
TD	TEMPORAL DEMAND
EF	EFFORT
OP	PERFORMANCE
FR	FRUSTRATION

APPENDIX B- ANOVA TABLES FOR TRACKING DATA

2 x 2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS VELOCITY RMSE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	38.191	0.16	0.690
I	1	1720.511	7.32	0.012
CI	1	187.796	0.80	0.380
ERROR	28	235.163		
E	2	1352.811	51.00	0.0000
EC	2	12.932	0.49	0.594
EI	2	46.061	1.74	0.190
ECI	2	37.183	1.40	0.255
ERROR	56	26.528		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS POSITION RMSE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	622.152	4.59	0.050
ERROR	14	135.440		
E	2	449.565	38.69	0.0000
EI	2	51.506	4.43	0.021
ERROR	28	11.618		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS ACCELERATION RMSE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	1309.177	5.56	0.034
ERROR	14	235.650		
E	2	716.463	28.63	0.0000
EI	2	17.063	0.68	0.484
ERROR	28	25.029		

2 x 2 ANALYSIS OF VARIANCE FOR VELOCITY RMSE DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	113.818	1.19	0.286
I	1	631.759	6.58	0.016
CI	1	121.342	1.26	0.271
ERROR	28	96.031		

ONE-WAY ANALYSIS OF VARIANCE FOR POSITION RMSE DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	211.722	5.45	0.035
ERROR	14	38.840		

ONE-WAY ANALYSIS OF VARIANCE FOR ACCELERATION RMSE DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	2657.418	17.97	0.0035
ERROR	14	147.893		

2 x 2 ANALYSIS OF VARIANCE FOR VELOCITY RMSE TRADE-OFF

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	50.476	0.62	0.437
I	1	68.416	0.84	0.366
CI	1	141.078	1.74	0.198
ERROR	28	81.147		

ONE-WAY ANALYSIS OF VARIANCE FOR POSITION RMSE TRADE-OFF

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	7.896	0.30	0.592
ERROR	14	26.278		

ONE-WAY ANALYSIS OF VARIANCE FOR ACCELERATION RMSE TRADE-OFF

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	7.896	0.30	0.592
ERROR	14	26.278		

2 x 2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS VELOCITY CONTROL SPEED

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	3.443	0.05	0.817
I	1	347.244	5.52	0.026
CI	1	261.096	4.15	0.051
ERROR	28	62.873		
E	2	110.480	9.94	0.0003
EC	2	15.042	1.35	0.267
EI	2	0.685	0.06	0.935
ECI	2	9.543	0.86	0.425
ERROR	56	11.110		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS POSITION CONTROL SPEED

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	4.014	0.43	0.521
ERROR	14	9.279		
E	2	10.714	6.07	0.010
EI	2	4.139	2.34	0.125
ERROR	28	1.766		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS ACCELERATION CONTROL SPEED

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	1330.043	6.70	0.021
ERROR	14	198.469		
E	2	51.547	4.27	0.024
EI	2	38.055	3.15	0.058
ERROR	28	12.070		

2 x 2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS VELOCITY GAIN INTERCEPT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	598.291	10.28	0.003
I	1	32.63	0.56	0.460
CI	1	380.358	6.54	0.016
ERROR	28	58.178		
E	2	181.196	25.66	0.0000
EC	2	18.415	2.61	0.084
EI	2	14.414	2.04	0.141
ECI	2	3.098	0.44	0.642
ERROR	56	7.062		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS POSITION GAIN INTERCEPT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	27.243	0.68	0.423
ERROR	14	39.909		
E	2	238.236	25.42	0.0000
EI	2	0.816	0.09	0.917
ERROR	28	9.372		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS ACCELERATION GAIN INTERCEPT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	66.008	3.37	0.088
ERROR	14	19.568		
E	2	33.516	5.21	0.021
EI	2	6.022	0.94	0.383
ERROR	28	6.431		

2 x 2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS VELOCITY GAIN SLOPE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	551.512	19.43	0.0001
I	1	0.956	0.03	0.856
CI	1	33.570	1.18	0.286
ERROR	28	28.391		
E	2	12.694	2.86	0.066
EC	2	9.353	2.11	0.131
EI	2	21.684	4.89	0.011
ECI	2	4.715	1.06	0.352
ERROR	56	4.435		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS POSITION GAIN SLOPE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	48.757	1.16	0.300
ERROR	14	42.143		
E	2	87.936	19.47	0.0000
EI	2	3.966	0.88	0.427
ERROR	28	4.516		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS ACCELERATION GAIN SLOPE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	4.346	0.17	0.685
ERROR	14	25.264		
E	2	21.790	2.03	0.150
EI	2	8.873	0.83	0.448
ERROR	28	10.723		

2 x 2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS VELOCITY PHASE INTERCEPT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	4366.483	13.48	0.0010
I	1	30.194	0.09	0.762
CI	1	3519.008	10.86	0.003
ERROR	28	323.910		
E	2	18.150	0.45	0.619
EC	2	94.555	2.36	0.110
EI	2	447.536	11.16	0.0002
ECI	2	103.348	2.58	0.091
ERROR	2246.08766	56 40.10871		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS POSITION PHASE INTERCEPT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	353.495	0.96	0.344
ERROR	14	369.084		
E	2	655.793	2.31	0.118
EI	2	187.284	0.66	0.525
ERROR	28	284.270		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS ACCELERATION PHASE INTERCEPT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	318.136	0.46	0.511
ERROR	14	698.500		
E	2	758.826	6.83	0.004
EI	2	94.416	0.85	0.438
ERROR	28	111.135		

2 x 2 ANALYSIS OF VARIANCE FOR VELOCITY PHASE INTERCEPT DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	125.401	0.41	0.528
I	1	760.343	2.47	0.127
CI	1	1537.231	5.00	0.034
ERROR	28	307.726		

ONE-WAY ANALYSIS OF VARIANCE FOR POSITION PHASE INTERCEPT DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	390.190	0.43	0.522
ERROR	14	904.914		

ONE-WAY ANALYSIS OF VARIANCE FOR ACCELERATION PHASE INTERCEPT DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	1336.432	4.57	0.050
ERROR	14	292.251		

2 x 2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS VELOCITY PHASE SLOPE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	23.401	1.23	0.278
I	1	12.820	0.67	0.420
CI	1	58.908	3.08	0.090
ERROR	28	19.097		
E	2	0.129	0.07	0.922
EC	2	0.523	0.30	0.732
EI	2	1.57	0.91	0.407
ECI	2	5.488	3.17	0.052
ERROR	56	1.734		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS POSITION PHASE SLOPE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	13.450	0.84	0.376
ERROR	14	16.054		
E	2	15.363	2.98	0.067
EI	2	3.270	0.64	0.537
ERROR	28	5.149		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS ACCELERATION PHASE SLOPE

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	3.464	0.04	0.838
ERROR	14	79.748		
E	2	70.943	5.93	0.007
EI	2	9.724	0.81	0.454
ERROR	28	11.967		

2 x 2 ANALYSIS OF VARIANCE FOR VELOCITY PHASE SLOPE DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	32.812	3.40	0.076
I	1	0.279	0.03	0.867
CI	1	21.410	2.22	0.148
ERROR	28	9.663		

ONE-WAY ANALYSIS OF VARIANCE FOR POSITION PHASE SLOPE DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	16.824	1.08	0.316
ERROR	14	15.527		

ONE-WAY ANALYSIS OF VARIANCE FOR ACCELERATION PHASE SLOPE DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	108.796	3.41	0.086
ERROR	14	31.869		

2 x 2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS VELOCITY RESPONSE HOLD

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	10997865.094	4.58	0.041
I	1	562581.260	0.23	0.632
CI	1	14532262.510	6.06	0.020
ERROR	28	2399166.802		
E	2	3091147.885	11.95	0.0000
EC	2	1032836.719	3.99	0.024
EI	2	140135.323	0.54	0.585
ECI	2	344292.948	1.33	0.273
ERROR	56	258598.052		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS POSITION RESPONSE HOLD

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	1404936.333	1.24	0.285
ERROR	14	1135935.970		
E	2	1051056.771	10.60	0.0004
EI	2	741446.271	7.47	0.003
ERROR	28	99202.926		

2 x 3 MIXED ANALYSIS OF VARIANCE FOR DUAL-AXIS ACCELERATION RESPONSE HOLD

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	499392.000	0.20	0.660
ERROR	14	2473564.262		
E	2	736512.938	3.03	0.064
EI	2	251758.563	1.04	0.368
ERROR	28	242957.726		

2 x 2 ANALYSIS OF VARIANCE FOR VELOCITY RESPONSE HOLD DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
C	1	3982905.375	1.00	0.327
I	1	1840388.167	0.46	0.503
CI	1	3796126.042	0.95	0.338
ERROR	28	3992682.253		

ONE-WAY ANALYSIS OF VARIANCE FOR POSITION RESPONSE HOLD DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	2214.083	0.00	0.973
ERROR	14	1901722.327		

ONE-WAY ANALYSIS OF VARIANCE FOR ACCELERATION RESPONSE HOLD DECREMENT

SOURCE	D.F.	MEAN SQ.	F.	PROB.
I	1	1291992.188	0.34	0.567
ERROR	14	3750789.235		

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