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Acknowledgement Response and Interference Timing During the Processing of Voice and Datalink ATC Commands

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ABSTRACT

ACKNOWLEDGEMENT RESPONSE AND INTERFERENCE TIMING DURING THE PROCESSING OF VOICE AND DATALINK ATC COMMANDS

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In aviation, effective communication between air traffic control (ATC) and pilots is critical to pilot performance and safety. Problems and limitations of current radio communications initiated the development of datalink technology. Datalink is a text system used to send messages between ATC and pilots. Although datalink was intended to reduce errors associated with radio communication, there are new concerns related to changes in information processing demands associated with executing speech and text ATC commands. In addition, the nature of responses differs between voice and datalink systems. In a voice environment, responses are immediate. However, time delays exist with datalink. These time delays may create an opportunity for interference. Therefore, the timing of interference and the acknowledgement response on command execution performance were examined during the processing of simulated ATC commands. Verbal and central executive (CE) interference tasks were presented before or after the acknowledgement. Participants received both speech and text commands, responded by a verbal or manual acknowledgement, and set the controls in a flight simulator. Results demonstrated no differences between speech and text formats with a verbal acknowledgement. However, there was an advantage for a manual acknowledgement with longer messages. Regarding interference timing, CE as opposed to verbal interference prior to an acknowledgement had a greater negative effect on control setting

performance and the magnitude of this effect was larger in the text condition. Thus, text information appears to be more susceptible to the negative effects of interference as resources begin to reach capacity. However, the differences between the sources of interference decreased with an increase in message length. Therefore, the timing and type of interference can have differential effects on resource capacity and the ability to rehearse information in memory. It was also suggested that the processing code of a task is of more importance than the response code. The findings are interpreted within the context of a working memory and resource perspective and implications are discussed with regard to the communication process in aviation.

This dissertation is dedicated to the memory of my father, Rev. Richard J. Risser.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

Table Page

LIST OF FIGURES

INTRODUCTION

Communication is a process whereby the exchange of information results in a shared understanding between two or more parties. In the context of aviation, the communication process between air traffic control (ATC) and the flight deck involves five stages: message transmission, reception, comprehension, acknowledgement, and execution. Further, messages sent by ATC to the flight deck must be read back to ATC as confirmation before executing the commands.

This communication process is critical to the efficacy and safety of aviation. Specifically, as the National Airspace System (NAS) becomes more congested, communication between ATC and the flight deck is becoming more important. The current method of communication between pilots and ATC uses radio telephony. Using the radio, the controller must ensure that each ATC message proceeds through all five stages of communication. Safety may be compromised when a single controller must coordinate and communicate with several aircraft at one time. For example, in a busy sector, a controller may communicate with as many as 25 aircraft. Thus, limitations of radio communications are becoming more apparent and potentially dangerous as air traffic increases.

The importance of communication is evident in the following set of examples from the Aviation Safety Reporting System (ASRS). This database is an anonymous reporting system established by NASA and the FAA. These reports are submitted by the aircrew to identify incidents and potential hazards and demonstrate some of the problems

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related to radio communications.

- ACN 442992: In a foreign country, a verbal departure clearance was issued in which the navigational fixes conflicted with the flight plan and actually sent the aircraft in the wrong direction. The flight crew concluded that English pronunciations of the two words (L'Aigle and Lagil) were too similar to be used safely in issuing departure clearances. They suggested that crews request a phonetic spelling of questionable fixes. A similar event occurred in ACN 432596 where the fix L'Aigle and L'Amoga were confused. The pilot stated that it is not uncommon to request clarification two or three times in a foreign country (ASRS, 2000).
- ACN 445811: A Cessna was performing touch and go landings when ATC advised of traffic in the area. There was miscommunication between the Cessna and the controller regarding the approach leg. The pilot of the Cessna did not see the traffic until it was directly in front of them. The pilot heard, "Fly the downwind at 1100 ft" but did not hear "extend downwind". It is possible there was a block (dual transmission) on the radio when ATC gave instructions and the pilot only received partial instructions (ASRS, 2000).
- ACN 559669: A B747-200 flight crew crossed an active runway because they responded to a similar call number of another aircraft. The three crew members believed they heard their call sign to cross (ASRS, 2003).
- ACN 442170: While flying at 7000 ft, the pilot thought he heard a clearance to 6000 ft. The pilot performed a readback and at 6500 ft the controller told him to maintain 7000 ft. The crew believed that the descent was cleared for another

aircraft with a similar call sign. They concluded that the error was due to high ATC workload and multiple radio frequency usage. A similar situation occurred in ACN 435953 where one aircraft took the descent clearance of another aircraft with a similar call sign. However, this incident was attributed to wind noise in a small jet in addition to radio frequency congestion (ASRS, 2000).

These excerpts from the ASRS database suggest that there are problems with language interpretation, clarity, radio congestion (blocked transmissions), confusion, readback errors, and extraneous environmental noise which can all lead to misunderstandings during message reception. It is important to note that the communication process is affected by both mechanical/technological characteristics as well as those imposed by human information processing. Problems at the message transmission stage can be the result of technical or environmental factors. The reception stage can be affected by technical issues or human perceptual factors. However, the later stages of the communication process (i.e., comprehension, acknowledgement, and execution) are dependent on human information processing. The following ASRS database summaries are examples of incidents that may have resulted from human errors in information processing:

- ACN 546528: On a go-around approach, ATC asked the pilots if they saw an aircraft in front of them. Due to an instrument approach, they responded that they could not the see the plane. They received instructions from ATC. The first officer incorrectly heard "Heading 280" instead of "Heading 250" and put the wrong number into the mode control panel. This action resulted in a slight deviation off course and a TCAS II warning of the aircraft in the area. They

attributed this error to distraction from searching for the other aircraft and trying determine how they lost separation (ASRS, 2003).

- ACN 557487: An altitude miscommunication occurred when the pilots thought they were cleared to 2000 ft for an approach. However, the actual clearance was 3000 ft. The crew attributed this error to being "busy" during the approach (ASRS, 2003).
- ACN 561950: During a climb to FL370, the pilots became concerned about storms ahead. They contacted ATC for a minor route change and ATC requested they change altitude to FL330. Neither the captain nor the first officer reset the altitude to FL330. The first officer, who was flying, did not hear the amended altitude clearance and therefore did not repeat the information to the pilot per flight crew procedures. They attributed this error to distraction. They were focusing on the new route clearance, entering information into the flight management computer (FMC), and monitoring their distance from the storms (ASRS, 2003).
- ACN 563797: There was a potential conflict between two aircraft when the pilot responded to instructions for another company aircraft with a similar call sign on the same frequency during an altitude clearance (ASRS, 2003).
- ACN 443994: ATC gave incomplete abbreviated instructions resulting in confusion between maintain speed and maintain flight level. The numbers were also similar, 270 and 290 (ASRS, 2000).

These excerpts suggest that pilot distraction from processing other sources of information in the cockpit can adversely affect the comprehension and execution of ATC

commands. As shown in the examples, sources of distraction (interference) may come from route planning, monitoring information, and problem solving. In addition, there was confusion attributed to messages that sounded similar such as call signs of other aircraft and altitude values. As a result, incorrect information was entered into the flight system or there was a flight path deviation. Collectively, these incident reports imply that a different method of communication may be beneficial.

Datalink

Controller to pilot datalink communication has been developed to address some of the current communication problems in the NAS. Datalink technology enables ATC to communicate with the flight deck by uplinking text messages to the FMC on the aircraft. Messages are then displayed on the control display unit (CDU) in the cockpit and read by the pilots. Typically, the pilot not flying (PNF) reads and communicates the uplinked message to the pilot flying (PF). Datalink is currently used in conjunction with the radio and is not envisioned as a replacement. Further, until recently, datalink has only been used during transoceanic flights because there are fewer tasks to perform in the cockpit during these extended cruise phases of flight. However, it has now gained further approval for domestic use and is being evaluated by the Federal Aviation Administration's ATC center in Miami (Donoghue, 2002).

Researchers have described the changes introduced by datalink and their effect on communication (Kerns, 1991; 1999; Navarro & Sikorski, 1999). Several advantages of datalink over voice have been noted. For instance, datalink helps reduce radio traffic and can therefore minimize channel blocks and keep frequencies open for urgent requests. A new feature of datalink is the ability to enable automatic gating. This allows a datalink

message to be automatically loaded into the aircraft systems with very few key presses. It has been suggested that this procedure can minimize workload and errors associated with manual entry (Van Gent, 1995) and studies have shown that allowing pilots to gate datalink information directly into the FMS is beneficial so long as they maintain control (Knox & Scanlon, 1991; Waller, 1992). Another important benefit of datalink is its permanence. Once a message is received and opened, it can remain on the screen until information from the FMS is needed for some other activity. With voice communication, pilots must often rehearse or write down the requests given by ATC until they are acknowledged and executed. In addition, datalink messages are stored in a log and are available for later reference. Thus, datalink allows the flight crew to double check information if necessary. Last, datalink changes the communication intervals between the pilot and ATC. Although transaction times are generally lengthened, datalink allows for more efficient multitasking by enabling the pilot or controller to distribute their workload (Lozito, McGann, & Corker, 1993; Prinzo, 2001).

Not all of the changes associated with datalink, however, are necessarily positive. Datalink introduces changes to the communication process that may create a different set of problems. First, responses to datalink requests are not immediate as they are with voice. The delay associated with a datalink response is due to the time it takes to navigate menus, read an ATC message, and generate responses with button presses on the CDU. Further, it takes a lot more time to generate a downlink message (i.e., flight deck to ATC) with datalink than to communicate the same message by voice. Second, certain phases of flight such as approach and taxiing may be better served by voice communications than datalink because pilots need to be able to visually scan outside the

cockpit (Van Gent, 1995). Third, datalink reduces the party line effect (i.e., where pilots listen to one another transmitting information to ATC on shared radio frequencies) limiting their ability to create a mental picture of traffic and weather (Pritchett & Hansman, 1995; Van Gent, 1995). Fourth, increased head-down time is also of concern resulting from the requirement to interact with the CDU to read and send datalink messages. Fifth, although datalink has the ability to gate information directly into the FMS, there are concerns regarding complacency and reduced situation awareness. Specifically, due to the high level of automation, pilots may accept the ATC uplink information and load it into the FMS without cognitively processing the content of the message (Van Gent, 1995). Another problem with datalink concerns the delay in transmission times and how interruptions may affect information processing of concurrent tasks. It has been suggested that the longer transmission times may reduce efficiency. Finally, errors with setting radio frequencies are more prevalent with datalink messages (Van Gent, 1995) because there is no immediate auditory feedback. These types of errors are easily detected in a voice environment because nothing will be heard if the radio is set to the wrong frequency.

In addition to changing the mode of communication between the flight deck and ATC, datalink also changes the information processing requirements in the cockpit. For example, ATC messages must now be read, requiring crews to switch between reading messages and listening to them. Datalink can also help to reduce memory requirements because messages displayed on the CDU are more permanent. In addition, datalink requires more manual interaction with the CDU and fewer verbal responses than radio.

Introducing datalink as a new mode of communication raises concerns as to whether there may be differences in how pilots process information in speech and text formats. To examine further the implications for text versus speech processing, it is important to consider the context in which communication occurs. Within the cockpit there are always other types of information being processed concurrently. For example, information is continuously integrated not only from ATC communications but also from instruments, displays, other flight crew, radio traffic, navigation, planning, and visual scanning of the environment outside of the cockpit. The pilots' ability to process these various sources of information requires a finite amount of cognitive resources. More specifically, the pilot must allocate cognitive resources to the appropriate task at the appropriate time. Furthermore, the information that is acquired while allocating resources to the specific tasks requires the maintenance of that new information in working memory. The information that is stored in memory will be used to execute certain tasks (e.g., ATC commands). However, both the storage of information in memory and the execution responses use different pools of cognitive resources. In other words, there are multiple pools of resources that may be allocated to specific stages of information processing. Thus, it is necessary to investigate the processing of speech and text ATC commands among multiple tasks within the context of working memory and resource allocation.

Working Memory

Human memory refers to the mental processes needed to acquire and retain information for later retrieval and the mental storage system that enables these processes (James, 1890). The three major functions of the memory system are the acquisition of

information (encoding), storage, and the retrieval of information (Melton, 1963). Distinctions have been made to characterize three main types of memory: sensory memory, working memory, and long-term memory. Of interest to the present study is working memory, a dynamic buffer of current and recently attended to information where the intermediate results of memory processes are temporarily maintained. Information is received from both the sensory stores and long-term memory. Early studies demonstrated that individuals are unable to recall unrehearsed information in working memory after about 20 seconds (Brown, 1958; Peterson & Peterson, 1959). Thus, it is necessary to understand the factors that affect the maintenance of information in working memory.

One model that describes working memory was proposed by Baddeley and Hitch (1974). These researchers argue that working memory is comprised of three mechanisms; a phonological loop, a visuospatial sketchpad, and a limited capacity attentional controller, referred to as the central executive (CE) processor. The two former subsystems provide the central executive processor with sensory information. Each of these fundamental components is discussed in the following sections.

Phonological loop. The phonological loop is responsible for the temporary storage of acoustic and verbal information. It is comprised of two components, the phonological store and the articulatory rehearsal system. These two components work with one another to maintain information. Specifically, information in the store decays after about two seconds unless it is refreshed by the articulatory rehearsal system through subvocalization. It is assumed that information presented in the auditory channel has direct access to the phonological store while information in the visual channel gains

access via an articulatory control process. Both the storage and rehearsal components of the phonological loop reveal differences in how information is encoded by means of similar sounding information, length of words, and the ability to filter competing sources of speech.

One source of evidence for the storage component of the phonological loop has been demonstrated by the phonological similarity effect whereby items that sound similar result in degraded serial recall (Conrad & Hull, 1964). This effect occurs because similar items use the same code within the phonological loop which results in interference and subsequently degraded recall. The rehearsal component of the phonological loop has been demonstrated by the word length effect (Baddeley, Thompson, & Buchanan, 1975). This effect is characterized by the slower rehearsal of longer words, presumably because they take more time to pronounce or subvocalize. Consequently, recall can be degraded for longer words because they are unable to be rehearsed as quickly as shorter words. The third effect that provides evidence for the phonological loop concerns unattended speech. Specifically, unattended speech can interfere with the serial memory for other verbal information in the store (Salame & Baddeley, 1982). All of the previously described effects were demonstrated during single-task conditions. However, additional evidence for the phonological loop can be obtained by examining these same effects when another task is competing for resources and disrupting the storage and rehearsal processes.

Within the context of the working memory model, articulatory suppression has been used as a concurrent task to utilize articulatory control resources. This method requires the repetition of an irrelevant sound (e.g., “the”) in order to prevent rehearsal

which ultimately results in poorer recall performance. During articulatory suppression, the phonological similarity effect demonstrates storage differences between the auditory and visual presentation of verbal information. For example, articulatory suppression of visually presented material eliminates the phonological similarity effect, but auditory presentation does not. This suggests that visually presented verbal information is unable to directly access the phonological store and must rely on a separate code (i.e., visual) to store the information and consequently, does not produce phonological similarity effects. On the other hand, auditory information produces a phonological similarity effect and impairs performance because it has direct access to the phonological store (Baddeley, Lewis, & Vallar, 1984; Murray, 1968).

Similar reasoning can be applied to the rehearsal of information within the phonological loop. The rehearsal component of the phonological loop is further evidenced by the disappearance of the word length effect during articulatory suppression (Baddeley et al., 1975). As noted above, the word length effect results from the slower rehearsal of longer words. Articulatory suppression eliminates this effect because it prevents rehearsal. These effects imply that verbal information presented auditorily and visually (i.e., speech and text) may be processed and stored differently within the phonological loop.

Baddeley (2002), however, admits that there remains a lack of specificity regarding two aspects of the phonological loop. The first is whether short-term forgetting is a result of trace decay or interference. Trace decay is the natural degradation of information over time whereas interference is the disruption of memory or mental activity by another mental process. It has been argued that short-term forgetting may result from

a combination of both decay and interference whereby trace information is displaced by subsequent information within a limited capacity system (Waugh & Norman, 1965). Baddeley argues that trace decay may be interpreted as a form of interference attributed to a continuously active nervous system. In this case, longer delays between reception and recall leave information more susceptible to neural activity and therefore may lead to poorer memory.

The other specificity problem is a failure of the model to demonstrate how the serial order of incoming items is maintained in memory (Baddeley, 2002). Thus, a chaining model has been suggested as a means to explain serial recall (Murdock, 1993; Shiffrin & Cook, 1978). According to the chaining model, each item in a serial list evokes the next item by association. The model predicts that when one is asked to recall sequences containing alternating similar and dissimilar items, errors will occur on the dissimilar items. However, Henson, Norris, Page, and Baddeley (1996) observed a pattern of recall errors that was inconsistent with chaining models. Specifically, when individuals were presented with a serial list of alternating similar and dissimilar items (e.g., C, X, B, R, T, M), results demonstrated that the errors were made on only the similar items. In this case, similar items were those items that sounded the same (e.g., an /e/ sound). This is consistent with the phonological similarity effect. The differences between these theories of serial recall depend on the context, stimuli, and experimental manipulations. Thus, the nature of encoding and retrieving serial information is still unresolved (Baddeley, 2002).

Visuospatial sketchpad. Analogous to its verbal counterpart, the visuospatial sketchpad is theorized to maintain and manipulate visual and spatial information accessed

via the senses or LTM. The sketchpad component of this subsystem is thought to function as a link between visual and spatial information (Baddeley, 2002). Attempts have been made to try and distinguish between the visual and spatial components of this subsystem. Interference within the sketchpad has been demonstrated by having participants tap out a spatial pattern on keys which impaired visuospatial imagery (Baddeley & Lieberman, 1980). Alternatively, unattended visual patterns cause interference with the visual component of the subsystem (Logie, 1986). Of further interest is the ability of visuospatial rehearsal. Logie (1995) suggested that the spatial component of the subsystem was responsible for rehearsal. Baddeley (2002), however, suggests that maintenance rehearsal is performed using an attentional mechanism provided by the central executive.

Central executive. The third component of working memory model is the central executive processor. This component was originally hypothesized to be a limited capacity resource pool acting as a coordinating mechanism to send and receive information between the two subsystems. It was thought of as a convenient pool of general processing resources and little attention was paid to the control of action characteristics (Baddeley, 2002). However, the attentional control of action was addressed by Norman and Shallice (1986) with their model of the supervisory attentional subsystem (SAS). This model conceptualizes the use of horizontal threads that represent schemas from LTM and vertical threads that represent attentional modes that interact with the horizontal threads and modulate schema activation. The horizontal threads control the routine behaviors that do not require constant attention and are triggered by environmental cues or other schemas. The vertical threads are the higher-level

attentional processes that are used when schemas are insufficient to achieve the intended plan of action in critical or novel situations. The vertical threads then modify the intended plan of action set forth by schema activation. Using this conceptualization of attentional control of action, Baddeley (2002) elaborated on the attentional subprocesses of the central executive: focused attention, divided attention, and switching attention.

Focused attention. Baddeley (2002) argues that the capacity of the central executive to focus attention is an important feature. Robbins et al. (1996) studied the capacity of the central executive and focused attention with tasks designed to disrupt the phonological loop, the visuospatial sketchpad, and the central executive. They used the game of chess because it requires significant planning and decision making and therefore they assumed it places a large demand on central executive resources. They examined the level of disruption on memory for chess positions and choice of the next move (i.e., tactical planning) in both experts and novices. Their results showed no evidence of verbal working memory by means of articulatory suppression. Performance was impaired by a concurrent visuospatial task demonstrating that visual and spatial working memory was involved. However, performance was most impaired when participants were required to generate random digits and this was true for both experts and novices. The digit generation task is assumed to place heavy demands on the central executive, thus demonstrating the role of the central executive in the game of chess.

Divided attention. The second attentional process associated with the central executive is divided attention (Baddeley, 1996). Divided attention refers to the allocation of mental resources between separate tasks (Kahneman, 1973). Thus, with regard to the working memory model, the central executive is assumed to be responsible for allocating

attention between concurrent tasks. To demonstrate the role of the central executive in divided attention, Logie, Della Sala, Wynn, and Baddeley (2000, November) used a task requiring both the phonological loop (digit span) and the visuospatial sketchpad (pursuit tracking) in patients with Alzheimer's disease and compared findings with younger and older controls. The central executive was expected to coordinate attention between these two activities. Additionally, individuals with Alzheimer's disease are known to have difficulty with divided attention. The results demonstrated that simultaneous task performance was not affected by age, but was impaired in the Alzheimer patients. When the tasks were performed individually, even with increasing difficulty, there was no evidence of performance degradation. Therefore, it was concluded that the deleterious effect of performing the tasks concurrently in the Alzheimer's group was a failure of the central executive to properly coordinate the activities between the two subsystems. Consequently, Baddeley (2002) argued that there is a separate component of the central executive that supports divided attention.

Switching attention. Attention switching refers to the capacity to alternate program sets or instructions between two separate tasks. The concept of attention switching originated from studies demonstrating slowed performance when switching between tasks (Jersild, 1927; Spector & Biederman, 1976). More recently, it has been proposed that the capacity to switch attention is an important component of the central executive (Baddeley, 1996). However, it has also been demonstrated that the capacity to switch attention is not completely dependent on the central executive (Allport, Styles, & Hsieh, 1994). Further, evidence from Baddeley and colleagues (2001) suggests that although the central executive is required for attentional switching, the phonological loop

also seems to play an important role. Thus, the question still remains as to whether task switching is an exclusive executive process or a series of processes. A recent model of executive control in task switching offers a two-stage approach: goal-shifting and rule-activation stages (Rubinstein, Meyer, & Evans, 2001).

Episodic Buffer. The fourth role of the central executive is thought to be an interface between the phonological loop, visuospatial sketchpad, and LTM. A recent revision of the model introduces a new component called the episodic buffer (Baddeley, 2000). This buffer manages the exchange of information between the two subsystems and LTM. The integration of information from LTM (prior knowledge) with working memory has been noted as a limitation of the previous model. In a study by Baddeley and Andrade (2000), participants were required to form auditory and spatial mental images during articulatory and spatial suppression. It was found that spatial suppression reduced vividness judgments more on newly created images (in working memory) than those images generated from LTM. The vividness of mental imagery and the accuracy of those judgments reflect the integration of working memory and LTM. This was one piece of evidence suggesting that the current three-part model of working memory was not complete. The original model also assumed that the central executive was an attentional mechanism without storage capacity (Baddeley, 1996). However, Daneman and Carpenter (1980) ascertained that working memory was able to simultaneously process and store information. The working memory span methodology was used to test this process. Participants were required to read or listen to sentences in which the last word of each sentence had to be recalled. The span of words to be recalled varied from two to five. Both reading and listening spans correlated with three reading

comprehension measures. Participants with higher reading comprehension measures could more efficiently process and store information compared to those participants with lower reading comprehension measures. In short, the current model of working memory lacks the integration of information from the subsystems and LTM that allows for active manipulation and maintenance. The buffer assumes some of the functions that were once assigned to the central executive in the original model. The current position regarding the central executive is that it is not only a memory function but also an attentional mechanism (Baddeley & Logie, 1999). The retrieval process from the episodic buffer is achieved through the coordination of the central executive where multiple sources of information may be processed concurrently (Baddeley, 2002). This process is assumed to be analogous to a mental model whereby information can be manipulated for problem solving and planning future behavior. Thus, coordination by the central executive is consistent with the attentional control of action that activates schemas from LTM and higher-order processes in real time to address novel situations.

The revised model of working memory differs from the original model in two important ways. First, there is now assumed to be a bidirectional flow of information between the two subsystems (i.e., phonological loop and visuospatial sketchpad) and verbal and visual LTM. That is, the subsystems enable LTM to encode information from their stores as well as receive implicit knowledge from LTM. Second, an episodic buffer has been included that combines information from the subsystems with information from LTM. One important note, however, is that there is currently no direct link between the subsystems and the episodic buffer. It is still assumed that information within working memory is coordinated by the central executive (Baddeley, 2002).

Resource Perspective

Another approach to understanding information processing is from the perspective of resources. The concept behind this approach is that humans have a limited capacity for information processing. When we are required to perform more tasks or tasks of greater difficulty we use more resources.

Single Resource Concept. From the perspective of single-task performance, task difficulty is defined as the mental effort invested in a task to maintain a given level of performance. Further, increases in effort will use more mental resources and performance will increase with increases in effort on a task of fixed difficulty. Likewise, as task difficulty increases it is also necessary to increase the amount of effort needed to maintain the same level of performance (Wickens, 1991b). The relationship between performance and resources is known as the performance-resource function (PRF; Norman & Bobrow, 1975). This relationship helps to explain why tasks with varying levels of difficulty can elicit the same level of performance provided that effort is adjusted accordingly. Although it is assumed that more resources are invested as task difficulty increases, the PRF does not specifically account for task difficulty.

Wickens (1991b) provides a model that describes the relationship between performance (P), task difficulty (D), and resources (R), the PDR model, and is expressed as:

$$P = \frac{R}{D}$$

The PDR model describes the relationship among the three variables used to predict task performance. For example, performance will increase if task difficulty is low relative to the amount of available resources. Alternatively, if the available resources are lower than

the difficulty of the task then performance will decrease. Also, one variable can be held constant in order to validate the manipulation of another variable (i.e., holding difficulty constant to measure performance as a function of change in resources).

The single-resource concept suggests performance trade-off strategies. When a given level of performance is required of a task, there is a natural tendency to minimize effort (Wickens, 1991b). That is, people will choose to conserve effort at the expense of maximizing performance.

It has been argued that the single resource concept results in a bottleneck within the information processing system because resources are allocated to one task or another and are not shared (Pashler, 1989). That is, information is processed in a serial fashion using a central pool of resources. Another argument by Kahneman (1973) consistent with the single-task resource view is that resources are available to other tasks in continuous and graded quantities as demonstrated by the PRF described above. Wickens (1991b), however, points out that the PDR model is based on single-task performance and does not necessarily predict dual-task interference.

Dual-Task Performance. Dual-task performance refers to the simultaneous execution of two tasks. There are several characteristics of resources that are relevant to dual-task performance: scarcity, allocation, and task difficulty (Wickens, 1991b). Scarcity is the foundation for all dual-task studies. Specifically, if resources are limited and divided between two tasks then performance will decrease on one or both tasks.

The allocation of resources implies that they can be assigned voluntarily in continuous and graded quantities. If resources are withdrawn from one task they can then be used to increase performance on a second task. This has been demonstrated by the

manipulation of instructions to reallocate effort between two tasks (Gopher, Brickner, & Navon, 1982; Vidulich, 1988; Wickens, Sandry, & Vidulich, 1983). The resulting performance of two tasks plotted against each other can be represented as the performance operating characteristic (POC; Norman & Bobrow, 1975). This graph represents the percentage of resources allocated to each task. There are two characteristics that may be revealed as a function of this plot: resource-limited regions and data-limited regions (Norman & Bobrow, 1975). Resource-limited regions are areas that demonstrate an improvement in performance as more resources are invested. Data-limited regions are characterized by areas where a constant level of performance is observed even as more resources are invested. Data-limited tasks are those that tend to be easy or are performed by highly skilled individuals.

The relationship of task difficulty to performance and resources in the single resource PDR model can also be applied to dual-task performance. With respect to the PRF, an increase in task difficulty will lower the PRF values. In this case, more resources are required to maintain performance at a constant level. Thus, there will be fewer resources available to the secondary task and performance will decrease. On the other hand, if resources on the secondary task remain constant and there is an increased demand for resources on the primary task, there will be fewer resources as a result and performance will decrease on the primary task (Wickens, 1991b). This can be described as the difficulty-performance trade-off where performance on one task decreases as the difficulty of the primary task increases (Wickens, 1980).

Of interest are two exceptions to the PDR model where the difficulty-performance trade-off is not obtained. These are both referred to as difficulty insensitivity (Wickens,

1984). The first exception, as already discussed, occurs when one task is data limited. In this case, allocating more resources to another task will not affect performance on the data-limited task because it does not benefit from investing any more resources. The second exception occurs when the two tasks are qualitatively different. These tasks can be described as using separate resources and can not be characterized by the difficulty-performance trade-off.

Multiple-Resource Theory

Elaborating on the concept of limited resources and the characteristics of dual-task performance, multiple-resource theory is a structural perspective of processing mechanisms. According to multiple-resource theory, there is not an undifferentiated pool of resources; rather, separate resources are available to different stages of processing and types of information. Characteristics of concurrent task processing that either aid or inhibit performance include confusion, cooperation, and competition for resources (Wickens, 1991b, 2000). The multiple-resource concept has also been utilized to explain difficulty insensitivity as described above (Kantowitz & Knight, 1976; Navon & Gopher, 1979). Wickens (1980) also noted two other characteristics of timesharing performance: structural alteration effects and perfect timesharing. Structural alteration effects are revealed when the structure of one task is altered while its difficulty remains constant and the degree of change is observed in the concurrent task. Perfect timesharing occurs when two tasks of constant difficulty are performed concurrently with no decrease in performance.

The combinations of difficulty insensitivity, structural alteration effects, and perfect timesharing have revealed three structural dichotomies in information processing.

Wickens' (1980; 1984; 1991b) multiple-resource theory makes the distinction between the stages of processing, codes of processing, and input modality. Processing stages refer to two separate resources of information processing: perceptual-cognitive activity (e.g., reading displays, monitoring, comprehension, diagnosis, or calculating) and response processes (e.g., control manipulation or voice output). A perceptual-cognitive task can be timeshared more effectively with a task that requires response processes. The second dichotomy refers to the codes of information processing: spatial and verbal. Spatial information can be timeshared effectively with a verbal task. This processing code dichotomy applies to perception (e.g., speech and text versus graphics and pictures), central processing (e.g., spatial working memory versus verbal working memory), and response processes (e.g., speech output versus manual response). The third dichotomy assumes different resources for visual and auditory input modalities, (e.g., speech versus reading text).

Processing stages. The multiple-resource concept introduces the dichotomy of perceptual and cognitive activity versus response activity. This can also be thought of as early and late stages of information processing, respectively. Specifically, tasks that utilize perceptual-cognitive resources and response resources separately can be timeshared more efficiently than tasks that share the same resource. For example, Wickens (1976) demonstrated that a tracking task and an auditory signal detection task, both of high difficulty, could be performed together effectively. On the other hand, degraded performance was observed when the tracking task was paired with a manual response task (maintaining a constant force). Another study demonstrated the separation of processing stages by evaluating speech production and comprehension (Shallice,

McLeod, & Lewis, 1985). The data showed greater interference between two tasks that required overt or covert articulation (response activity) or two tasks that required speech detection and recognition (perceptual-cognitive activity). Thus, tasks that drew upon separate processing stages did not show the same interference as those that required the same processing stage.

Processing codes. The second dichotomy from a multiple-resource perspective is one of processing codes. Verbal and spatial information are assumed to use different resources. The processing codes are relevant to three stages of information processing: perception, central processing, and response processes.

The processing code dichotomy related to perception is relevant to the display of verbal (e.g., speech and text) and spatial information (e.g., analog representations and spatial orientations). However, this stage can be somewhat ambiguous because evidence exists that certain spatial representations (e.g., pictures and geometric symbols) are able to produce verbal labels (Robinson & Eberts, 1987).

The processing code dichotomy can be expanded further within central processing and working memory operations. According to multiple-resource theory, working memory is responsible for the storage and rehearsal of words and digits (verbal processes) and visual, spatial, or navigational information (spatial processes). Other models have also demonstrated similar dichotomies between verbal and spatial information during central processing (Baddeley & Hitch, 1974). As with the perceptual stage of information processing, ambiguity also exists between verbal and spatial codes during central processing. For example, an air traffic controller may direct a plane based on mathematical calculations or by visualizing a vector to determine the correct heading

(Weinstein, 1987). Additionally, navigational information may be maintained in working memory as a verbal list of commands or a mental image of the path (Wickens, 1991a). Therefore, it is necessary to understand that certain tasks may be performed effectively by utilizing different strategies. It may be the case, and consistent with the idea of difficulty as described earlier in dual-task performance, that a task can be performed effectively with less effort by employing a different processing strategy. For example, expert users may rely on mental models for accomplishing their tasks whereas novice users may employ a less effective strategy. Specifically, when given navigational instructions, experts may transform and encode navigational information using a spatial code whereas novices may utilize a verbal code by maintaining the instructions in their original form.

With respect to response processes, the dichotomy between verbal and spatial information can be demonstrated with speech responses that utilize the verbal code and manual responses that utilize the spatial code. Wickens (1991b) argues that manual responses use a spatial code because the interfaces (i.e., mouse and keyboard) are arranged in a spatial manner. Studies have demonstrated greater interference between two manual response tasks than between a manual and speech response task (Vidulich, 1988; Wickens, 1980; Wickens & Liu, 1988).

Thus far, multiple-resource theory has demonstrated the structural dichotomies of processing stages (central processing and response activity) and processing codes (verbal and spatial). In addition, resource allocation and subsequent timesharing performance have been noted within each dichotomy. However, the value of multiple-resource theory exists in its ability to predict task performance based on all stages of information

processing, including interactions between dichotomies.

Interaction of codes and stages. Multiple-resource theory predicts that interference between two tasks will increase if they both utilize verbal or spatial processes. Furthermore, interference will be greater when similar codes are processed within the same stage rather than between stages (Wickens, 1991b). The interaction of codes and stages can be represented in a 2 x 2 matrix. Examples of tasks related to both stages and codes are shown in Table 1.

Table 1
Tasks Characterized by the Interaction between Stages and Codes of Processing

Code	Perceptual-Cognitive Stage	Response Stage
Verbal	Text comprehension Speech comprehension Rehearsal Mental arithmetic Logical reasoning	Speech
Spatial	Velocity flow fields Spatial relations Mental rotation Image transformations	Manual control Keyboard presses

Note. From *Multiple-task Performance* (p. 18), by C.D. Wickens, 1991, London: Taylor and Francis.

As depicted in Table 1, two tasks that share one or both dimensions within the matrix will result in degraded performance and difficulty-performance trade-offs. The interaction of the dichotomies within the matrix have been demonstrated by Wickens and Liu (1988). In one experiment, participants were required to perform a decision task that was characterized by verbal or spatial information. Specifically, they performed either arithmetic or visual angle addition. Information from previous trials had to be retained

and placed a continuous load on working memory. Consistent with multiple-resource theory, spatial performance was poorer with a manual (keypress) response and verbal performance was poorer with a speech response. These results demonstrate dual-task interference within codes and across processing stages. In a second experiment, participants performed each of the four task combinations (verbal or spatial task with a verbal or manual response) while performing a tracking task. The main result was that the spatial task combined with a manual response was negatively affected by interference from the tracking task. When task difficulty increased, performance on the spatial task but not the verbal task declined further. In contrast to the first experiment, these results demonstrate interference within processing stages and across processing codes. One finding of interest was that interference on the spatial tracking task decreased (i.e., performance improved) when verbal task demand increased. Consistent with Kahneman's (1973) single-resource model, Wickens and Liu (1988) suggested that an increase in verbal task demand also served to mobilize all resources within the system. Thus, without the need for verbal resources on the tracking task, more spatial resources were allocated to the tracking task during a period of higher demand.

Input modalities. The original multiple-resource model included a third resource dichotomy between auditory and visual input (Wickens, 1980, 1984). The model predicted that timesharing performance between two tasks would be better when they used different input modalities. However, Wickens (1991b) later questioned the strength of the input modality dichotomy. A reanalysis of the Wickens and Liu (1988) data revealed two results associated with different dual-task combinations. The first result is characterized as preemption and refers to a situation where a continuous visual task is

timeshared with either a discrete auditory or visual task. If the discrete task is auditory in nature, attention is drawn to the auditory task and preempts performance on the continuous visual task. Under these conditions, performance on the discrete auditory task is nearly the same as in single-task conditions and performance on the continuous task suffers – a form of cross-modal interference. However, this preemption does not occur with discrete visual tasks. Therefore, Wickens (1991b) concluded that a shift in task priorities occurs within the POC space whereby the discrete auditory task is favored over the continuous task. The second result is characterized as discrete task sharing. When two discrete tasks are presented simultaneously, there is little evidence of timesharing between the two tasks. Instead, they are performed serially regardless of modality (Wickens, 1987). Another factor that influences input modalities is visual scanning. A problem with scanning occurs when two visual stimuli can not be brought into foveal vision simultaneously. As a result, the perceptual quality of the stimuli may be degraded or there may be time delays – a form of intramodal interference. Therefore, if one of the stimuli is presented auditorily there should be a cross-modal display advantage suggesting that the two modalities use different resources. However, Wickens (1991b) argues that input modalities are not necessarily characterized as having resource capacities like those for codes and stages. One reason for this distinction is that the cross modal advantage is related more to structural mechanisms than central mechanisms of processing. Further, when task demands change, input modalities do not reflect the same changes in physiological arousal observed with codes and stages. Specifically, as task demands increase there is a corresponding need to increase effort. This increase in effort is assumed to be the result of physiological arousal associated with consolidation of

central resources. The auditory and visual channels do not have the same capacity to respond to increases in arousal. Although the effects of input modality may be limited in dual-task performance, they may still play a role in activities such as task switching, resource cooperation, and confusion.

Task Switching

Models of working memory and multiple resources are generally concerned with concurrent-task performance in an attempt to explain the underlying mechanisms of information processing. Although many tasks are performed concurrently, there are other instances when they are performed in rapid alternation. As previously discussed, the combination of two or more tasks requires the distribution of resources among tasks. The resources can be allocated in either a graded or discrete fashion. Graded resource allocation occurs when some portion of cognitive resources are assigned to the primary task and another portion to a secondary task. On the other hand, discrete allocation refers to the switching of attention and resources completely between tasks (Wickens, 2000). Therefore, information processing demands of rapidly alternating tasks may share similar limitations with simultaneous task demands. For both concurrent-task performance and task-switching performance, the limitations of information processing are modulated by the cognitive demands of the individual tasks. For instance, a difficult primary task might allow fewer resources to be allocated to an easier secondary task. Kahneman (1973) originally proposed that a closed-loop system was responsible for monitoring task demands and allocating the necessary mental resources as demands changed. Thus, rapid task switching would require the continuous reallocation of cognitive resources between two tasks as it does for concurrent-task performance. During multiple-task performance,

the allocation of resources between tasks can be considered an emergent property of information processing. Therefore, it is necessary to understand how memory, task characteristics, and mental resources interact to account for performance in multitask environments such as aviation.

Given the activities, rules, and procedures of the cockpit, much of the information processing related to communications may not always require simultaneous processing of information as much as it would the ability to quickly alternate tasks (i.e., task switching). In other words, information in the cockpit may also be processed in sequence. For instance, a pilot may listen to radio traffic in the area, communicate with ATC, stop and perform a scan of the instrument panel, and then resume communicating with ATC. In this case, a set of instructions and resources are allocated to a single task before switching to a second set of instructions and resources for a subsequent task. Thus, when resources and cognitive programs (or a set of instructions) alternate between tasks, it is referred to as task switching. Task switching depends more on the execution of a cognitive program associated with a task in working memory than on continuous concurrent-task performance.

Errors that occur in task switching have been said to result from a failure of attentional monitoring (Reason, 1990). These errors may manifest themselves as either slips or lapses. Slips are observable actions that are not executed as planned. In contrast, lapses are a more covert type of error involving a memory failure which may not be directly observable. Slips are associated with execution failures while lapses are associated with failures in storage. Reason argues that to avoid such errors, it is necessary to initiate cognitive checks to ensure that actions taken were consistent with the

intended plan. Initiating cognitive checks becomes more critical when the actions require one to deviate from a routine behavior or perform a task involving automatic processing. The internal checks require that information in working memory be brought into the attentional control loop for review. Reason suggests that failures of attentional checking occur as a result of inattention (omitting a necessary check) and overattention (making a check at an inappropriate time). Thus, slips occur during the lack of attentional monitoring. Most errors occur after the central processing stage when the consequences of one's actions are observable and the individual makes a subsequent corrective action (as noted in several of the previously mentioned ASRS reports).

Some evidence of task switching supports Reason's (1990) concept of attentional checks. Baddeley, Chincotta, and Adlam (2001) examined the effects of interference on task switching by creating cognitive programs (e.g., instruction sets) associated with the addition and subtraction of numbers. The primary task included lists of numbers to be added and subtracted. They were presented in blocks requiring all addition, all subtraction, or blocks in which problems alternated between addition and subtraction. Another variable studied was the presence or absence of cues. One condition included cues (+ and – signs) in the arithmetic problems and the other condition did not, thereby requiring individuals to maintain the instructions in memory. Both verbal and CE secondary tasks were used to create interference with the instructions in working memory. The verbal task used articulatory suppression requiring participants to recite short, well learned sequences including days of the week and months of the year (e.g., Monday, Tuesday, Wednesday or January, February, March). The CE task was a verbal task that required participants to recite alternating days and months in sequence (e.g.,

Wednesday, July, Thursday, August, Friday, September). This task required executive resources because attentional control was needed to maintain list order and alternate sequences in memory. The results demonstrated that when cues to alternating arithmetic problems were absent, and the individual was required to maintain the instruction set in memory, there was an effect of articulatory suppression suggesting that subvocalization of the instruction set for task switching interferes with the phonological loop. The CE task also negatively affected the maintenance of the switching program in working memory in addition to primary task performance. Thus, the results demonstrated the cost of task switching and the role of verbal control in executive processes.

By definition, task switching does not involve timesharing resources; thus, one could argue that multiple-resource theory does not apply. However, Wickens (1991b) offers two reasons why task switching may involve shared resources. First, when the discrete actions for two tasks do not overlap in time, but require one to maintain prior task actions in memory, the processing code for the task is maintained in memory and is susceptible to interference from a secondary task. Second, responses made during task switching may reflect differences in the switching distance (e.g., the extent that two tasks share resources) within and between the multiple resource dichotomies. Wickens suggests that when the switching distance increases within a resource boundary it slows switching and when the distance decreases between resources it speeds switching.

Resource Similarity

Although a multiple resource perspective can explain most dual-task performance decrements, there are exceptions that are related to the degree of similarity between tasks. For example, cooperation and confusion are emergent features of dual-task performance

and arise from the similarity between tasks. Performance on two competing tasks that are similar may either improve due to cooperation or decline due to confusion. In the first context, cooperation between two similar tasks is the result of a common mental set, processing routine, or timing mechanism (Wickens, 1991b). For example, performance on two simultaneous tracking tasks is better when the dynamics underlying each task are similar (Chernikoff, Duey, & Taylor, 1960). This phenomenon has also been shown in rhythmic tasks where timesharing performance is better when rhythms are similar (Duncan, 1979). Wickens (1991b) notes that the similarity of the information processing routines between the tasks improves performance by facilitating cooperation.

In contrast, two tasks that are similar may also result in confusion which can impair performance. Confusion is associated with similarity between task characteristics rather than between resources. Confusion or cross-talk occurs when the responses for one task are activated by stimuli for a another task (Wickens, 1991b). Confusion has also been referred to as outcome conflict (Navon, 1984). A classic example of confusion occurs in the Stroop task where the semantic characteristics of a color word (yellow) interfere with the ability to report the actual color of the printed word (Stroop, 1935). However, the Stroop task does not require divided attention between multiple tasks. To determine if confusion is responsible for task interference, Wickens (1991b) suggests examining the similarity of the tasks and determining if the manipulation of one task directly influences response errors in another task. In other words, confusion may be the result of misdirected output from the properties or characteristics of one task that negatively affects performance on a second task.

The distinction between resource competition and confusion depends on task

characteristics. Resource theory best describes interference related to the difficulty-performance trade-off. On the other hand, confusion describes tasks along dimensions of similarity such as closeness in space or semantic meaning. Furthermore, there is a distinction between confusion and cooperation. When central processing routines for two tasks are more similar, performance may increase through cooperation. Alternatively, when the semantic or physical representation of task information is more similar, performance may decrease through confusion (Wickens, 1991b). For example, if two tasks have similar cognitive programs, this reduces the switching distance, and may facilitate cooperation (e.g., two spatial tasks requiring distance estimation). However, if two tasks share a similar physical representation or meaning (e.g., two similar looking displays with different purposes or two different looking displays with similar purposes) performance may decrease through confusion.

Comparison of WM and MRT

It has been argued that the limitations of working memory are responsible for the information processing bottleneck (Carswell & Stephens, 2001). However, the limiting factor is not working memory capacity alone, but also available processing resources at various stages of information processing. Baddeley and Hitch's (1974) working memory model and Wickens' (1984) multiple-resource theory can be compared along capacity and processing resource dimensions.

Both multiple-resource theory and the working memory model suggest that performance will decrease when concurrent tasks share the same processing code and increase when tasks use separate codes. Specifically, the theories are similar with respect to the differentiation between verbal and spatial processing codes during the central

processing stage. As previously discussed, the dichotomy of input modalities within multiple-resource theory has limitations (Wickens, 1991b). The limitations are related to the capacity and physiological arousal of information processing resources. Visual and auditory inputs do not appear to have a capacity similar to that of codes and stages. Therefore, input modalities are now considered less important for interpreting dual-task performance, as they are considered to be structural limitations rather than central processing limitations. Similarly, the working memory model does not include input modalities as a separate resource.

The two theories differ with respect to how information is processed and stored. Multiple-resource theory is an information processing theory that specifies information flow associated with limited capacity resources during input, central processing, and response stages of processing (e.g., an input-process-output model). The working memory model places more emphasis on the storage and rehearsal of information during central processing. However, multiple-resource theory makes an additional distinction between processing stages and includes a response stage. Furthermore, multiple-resource theory specifies the processing stages and their interaction with codes. Understanding the interactions between codes and stages is critical when interpreting measures of human performance. During multiple-task performance, individuals are not only processing information but also simultaneously responding to information.

Another difference between the two theories concerns the central executive and its relationship to the control of attention. The working memory model incorporates a central executive processor that utilizes significant resources for coordinating the two subsystems and information from LTM. The executive component of the working

memory model distinguishes itself from multiple-resource theory such that CE interference will cause an overall decrease in performance regardless of processing codes, stages, or modalities. However, the concept of an executive component in information processing in the working memory model does not preclude a similar component in multiple-resource theory. Although there have been criticisms of the multiple resources model (Navon, 1984), Wickens (1991b) provides two arguments for maintaining the idea of a single, undifferentiated resource. First, when task demands are high, one may utilize a strategy that involves other resources. For instance, if spatial task demands are high, individuals may resort to verbal coding of spatial information to maintain performance. The concept of recoding is consistent with Logie, Della Sala, Wynn, and Baddeley (2000) who found a visual similarity effect on memory span for verbal materials suggesting that visual and phonological information are being combined in some manner. Second, Wickens notes that when all task demands are high, an executive resource may be responsible for scheduling and selecting tasks. Although not explicitly spelled out in the multiple resource model, these two points are consistent with the central executive component of the working memory model (Baddeley et al., 2001; Baddeley, 2002; Baddeley & Hitch, 1974). Therefore, with respect to an executive controller, the models are only similar when resources are recoded or when multiple task demands are high.

The two theories are also similar with respect to the central processing of verbal and spatial codes. As previously discussed, verbal and spatial codes are the cognitive representations of how information is processed and stored. For verbal information, the working memory model requires the phonological loop and multiple-resource theory specifies a separate verbal resource capacity. For spatial information, the working

memory model requires the visuospatial sketchpad and multiple-resource theory specifies a separate spatial resource capacity. However, the models differ in that the working memory model is concerned with information storage and rehearsal whereas multiple-resource theory is concerned with information processing and response. Furthermore, interference operates by disrupting storage and rehearsal according to the working memory model and by exceeding capacity limitations according to the multiple resource perspective.

Although there is no single theory to encompass all aspects of information processing and human performance, these theories may compliment one another. In sum, there are many similarities between Baddeley and Hitch's (1974) working memory model and Wickens' (1984) multiple-resource theory, but there are also some important differences. Specifically, both theories predict that two tasks using the same resources will result in greater interference and performance decrements. However, multiple-resource theory makes a finer distinction between resources for processing codes and stages. The working memory model uniquely predicts that utilizing CE resources will limit the processing of multiple sources of information regardless of processing code.

Information Processing and Datalink

Baddeley and Hitch's (1974) working memory model and Wickens' (1984) multiple-resource theory may provide important insights into the changes in information processing requirements introduced by datalink. As noted above, datalink presents some ATC communications in text format as opposed to the traditional speech format afforded by radio. Thus, it introduces an additional visual processing requirement in an already

visually complex environment. On the other hand, voice communication relies on auditory resources that are used less frequently on the flight deck. Therefore, it is important to consider whether there are processing differences between speech and datalink ATC messages. Further, the working memory and information processing models can be used to determine whether speech and datalink messages are differentially affected by the need to perform other activities in the cockpit such as scanning displays and instruments, communication with the crew, navigation, planning, and decision making. Thus, speech and text processing may differ in their susceptibility to various sources of interference generated by these other activities.

Specifically, the working memory model would predict that additional sources of verbal information would interfere with speech ATC messages in the phonological loop. Likewise, visual interference would have a negative effect on processing datalink messages resulting from limitations of the visuospatial sketchpad. Finally, CE interference might affect speech and datalink messages similarly because it uses resources involved in the control of attention and the coordination of information in memory. Regarding multiple-resource theory, one might predict that processing two sources of information which share the same code would result in a decrease in performance. However, because multiple-resource theory makes a finer distinction between stages of processing, it might also predict that verbal information will interfere with *both* speech and datalink messages because they all share a common processing code. Furthermore, regarding datalink and multiple-resource theory, visual interference would result from structural interference (i.e., cost of visual scanning between two displays) rather than central processing limitations.

Task Interference and Input Modality

Recently, a series of studies was initiated to investigate whether speech and text processing are differentially affected by various sources of interference guided by the theories of Baddeley & Hitch (1974) and Wickens (1984). In the first study, Risser, McNamara, Baldwin, Scerbo, & Barshi (2002) used a recall paradigm in which they presented individuals with lists of words in either a speech or text format. The words had to be remembered in the context of CE, verbal, visual, or no interference. The CE interference task required participants to generate letters at random and say them aloud. The verbal interference task required participants to correctly identify letters with an /ee/ sound (e.g., V, T, D) and the visual interference task required participants to correctly identify letters that contained a curved shape (e.g., S, U, and C). Both verbal and visual interference tasks were presented on the screen. There was also a control task in which words were recalled without any interference. Stimuli for the word and interference tasks were presented in an alternating manner (e.g., "house" – "C" – soldier – "T" – jewelry – "R"). After all of the words and letters in a set were presented, the participants wrote down as many words as they could recall. The primary performance measure was the proportion of words correctly recalled. Secondary measures included the proportion of correctly detected target letters and the proportion of commission errors (i.e., erroneous responses to nontarget letters). Based on the Baddeley and Hitch working memory model, the authors predicted that CE interference to be equally disruptive in both speech and text formats because it would utilize the most cognitive resources, thus limiting the processing of multiple sources of information and disrupting rehearsal. Additionally, the working memory model would predict that spoken words would be negatively affected

by verbal interference and text would be negatively affected by visual interference. However, multiple-resource theory would predict that *both* presentation formats would be equally affected by verbal interference because they share a common verbal processing code.

Consistent with the hypotheses, the results demonstrated that word recall was impaired the most by CE, followed by verbal, and then visual interference. An interaction between presentation format and interference task demonstrated that in the speech condition, only the CE task differed from the control task. However, in the text condition, all three interference tasks differed from the control task. When the analyses were limited to only verbal and visual interference, recall was impaired more in the text as compared to the speech condition and this difference was greater under verbal as compared to visual interference. The finding that verbal interference disrupted recall more than visual interference in the text condition was the opposite of initial expectations. The authors explained this result by appealing to multiple-resource theory. Specifically, both interference tasks used the visual channel; thus, interference occurred more in the text than in the speech format. According to the working memory model, verbal as opposed to visual interference had a greater negative effect on recall because both utilized the phonological loop and inhibited recall. Therefore, it is possible that the visual presentation of the verbal interference task required an extra step of processing and had an even greater negative effect on recall performance. It is important to note that Risser et al. (2002) can be criticized for the visual presentation of the verbal interference task because there was no direct intramodal comparison. Specifically, the working memory model suggests that speech information has direct access to the phonological

store. In addition, to be consistent with multiple-resource theory, the input modality for the interference tasks should be the same as for the primary task. The secondary-task performance (e.g., target identification for verbal and visual interference tasks) demonstrated no differences in the number of correct detections. However, more errors of commission were made in the verbal as compared to the visual interference task.

Collectively, these results suggest that information in a text rather than speech format may be more susceptible to interference. In addition, the negative effects of verbal interference suggest that both speech and text formats may share a common verbal code; however, text processing may require an extra step and extra resources to recode phonological information (i.e., from visual text information into the verbal code stored in the phonological loop) making it more susceptible to other forms of interference. These results suggest that there may be differences between speech and text processing in the cockpit. Processing secondary sources of information when a message is received may impair recall of the message content. Specifically, memory for datalink messages may be more likely to be disrupted by engaging in higher-order thinking such as planning or decision making and engaging in conversation or reading displays. Given these findings, it was necessary to reexamine these effects with a more ecologically valid approach using simulated ATC commands rather than word lists.

Task Interference, Input Modality, and Commands

In a second study, Risser, Scerbo, Baldwin, and McNamara (2003) used a paradigm similar to that of Risser et al. (2002), but with a simulated control panel and simulated ATC commands. The control panel included six graphic switch displays to be manipulated by a mouse. The controls consisted of two binary on/off switches, two

discrete 4-position dials, and sliding tabs on two continuous scales. They were labeled autopilot, lights, autobrakes, flaps, heading, and speed. Four 3-word command phrases were used (e.g., set heading 160) and presented in speech and text. To preserve consistency with Risser et al., each of the three command words were separated by the presentation of the interference task letters (e.g., "set" – C – "heading" – T – "160" – H). Procedural commands were used because they not only required working memory resources as in the previous study, but they also required the execution of that information. Commands were presented in speech and text formats in the context of CE, verbal, visual, and no interference. A second goal was to change the presentation of the verbal interference task from the visual format used in the previous experiment to an auditory format to be more consistent with multiple-resource theory. Thus, participants were required to *listen* for an /ee/ sound rather than *read* an /ee/ sound. The procedure for this experiment was similar to that of Risser et al. except that after receiving the commands and responding to the interference task, participants had to execute the commands in the correct order on the control panel. Primary task performance was measured by the proportion of controls correctly set in the correct order (CSCO) and erroneous responses to other controls not specified in the command set (FAOC).

The results demonstrated that both CSCO and FAOC performance was most affected by CE interference, followed by verbal, and then visual interference. Additionally, there was no difference between speech and text presentation formats on the CSCO measure. Compared to Risser et al. (2002), the main effects of interference were similar. Although there was no interaction between presentation format and interference task for control setting performance, there was an interaction with

secondary-task performance showing that verbal interference produced fewer correct detections than visual interference in the speech condition. Conversely, there were fewer correct detections for visual as compared to verbal interference in the text condition. The authors argued that the secondary-task results were consistent with Wickens' (1984) multiple-resource theory. Specifically, performance on a more difficult primary task was maintained at the expense of a less difficult secondary task. Thus, it was suggested that performance would be impaired on a secondary task so long as it is utilizes the same cognitive resources as the more difficult primary task. The authors concluded that CE, verbal, and visual processing can interfere with successful command execution; thus, it is important for pilots to consider task prioritization and execute ATC commands prior to processing other tasks in the cockpit.

In a third study, Scerbo, Risser, Baldwin, & McNamara (2003) used the same paradigm as in the previous study (Risser et al., 2003), however, the number of commands (i.e., message length) in a set was manipulated from two to four. By manipulating the number of commands, it was possible examine the effect of different levels of task demand. Specifically, an increase in the number of commands was hypothesized to increase the working memory load, thus maximizing the verbal resources of the phonological loop.

The results demonstrated that more commands were correctly set in the speech as compared to the text condition regardless of interference type. Once again, CE impaired control setting performance the most followed by verbal and visual interference. As expected, performance decreased with an increase in the number of commands. More importantly, the effect of message length was moderated by the source of interference.

Specifically, command length had no effect on control setting performance under CE interference (i.e., performance was equally poor across all command lengths). Under verbal interference, performance was lower for both the 3-command and 4-command sets compared to the 2-command set. However, under visual interference, performance differed for each command length where a decrease in performance was observed with an increase in command length. The FAOC data demonstrated that more errors were made when messages were presented in a text as compared to speech format; however, this effect was not moderated by interference type or message length. Collectively, the results demonstrated that as memory load increased, there were differential effects on performance as a function of the source of interference. Specifically, the decrease in performance associated with an increase in command length during verbal interference may reflect a greater disruption of the ability to rehearse and maintain commands in the phonological loop. Furthermore, fewer CSCO and more FAOC in the text as compared to the speech condition may suggest that memory for text is more susceptible to other forms of interference. Also, as in the previous control panel study (Risser et al., 2003), there was a modality dependent interaction for secondary-task performance where there were fewer correct detections during verbal as compared to visual interference in the speech condition. However, intramodal interference was not observed in the text condition.

Compared to the word recall study (Risser et al., 2002), the process of recalling and executing procedures in the two command studies (Risser et al., 2003; Scerbo et al., 2003) appeared to increase the demands on working memory. Consistent with multiple-resource theory, increased task demand was demonstrated by an intramodality

interference effect of verbal code on secondary-task performance. Although simulated ATC communications were used in the two command studies, the display configuration was not representative of the actual datalink environment. Thus, a subsequent study was conducted to address this display configuration issue.

In a fourth study, Risser, Scerbo, Baldwin, & McNamara (2004) used a paradigm similar to the previous two control setting studies (Risser et al., 2003; Scerbo et al., 2003), but with a more ecologically valid environment that included two displays: one for a desktop flight simulator with a simulated cockpit and one to represent an auxiliary CDU to display text messages. The additional display for text messages was expected to increase the load on the visual channel and subsequently result in intramodal interference. Furthermore, this study used prosodic speech by presenting complete command phrases followed by the set of interference stimuli (e.g., "set heading 160" – R – T – C), in contrast to previous studies where words in the command phrases alternated with interference task letters (Risser et al., 2003; Scerbo et al., 2003). Prosodic speech was used because it is more representative of actual ATC commands. Also, command lengths were limited to two and three because performance was so poor with four commands in the previous study. Once again, it was expected that CE and verbal interference would have the greatest negative effect on control setting performance. In addition, it was expected that there would be a negative effect of visual interference on control setting performance during the presentation of text messages given the visual complexity and scanning requirements of two displays.

The results demonstrated that longer message sets produced poorer performance as in the previous study (Scerbo et al., 2003). However, the effect of message length was

not dependent on interference type. It is possible that the prosodic speech facilitated the chunking of information in memory and therefore reduced working memory demands making more resources available for the secondary task. For CSCO performance, CE interference was the most disruptive followed by verbal and visual interference as in all three previous experiments (Risser et al., 2002; Risser et al., 2003; Scerbo et al., 2003). These findings were obtained in the absence of a modality effect suggesting that both the speech and text commands utilize an underlying verbal code and are therefore more susceptible to verbal interference. However, the FAOC data demonstrated that, once again, more errors were made in the text condition as compared to the speech condition. Furthermore, there was a modality dependent effect of interference where more errors were made under visual and CE interference when messages were presented as text compared to speech. The authors concluded that this effect resulted from an increase in visual scanning requirements between the two displays and that this additional source of interference was not present under verbal interference or in the speech condition because participants were able to view the cockpit while simultaneously listening to the information. Moreover, this additional visual scanning requirement was not present in the previous experiments (Risser et al., 2002; Risser et al., 2003; Scerbo et al., 2003) because all stimuli were presented on a single screen.

Collectively, the findings from Risser et al. (2003), Risser et al. (2004), and Scerbo et al. (2003) suggest that for ideal performance, the input modality (i.e., visual versus auditory) of verbal information (i.e., text or speech) is less important than the source of interference because both text and speech utilize an underlying verbal processing code. In particular, sources of interference that require the control of attention

or decision making (e.g., CE resources) and those that require the use of the phonological loop are of most concern because they disrupt the rehearsal process in memory. Furthermore, when errors in performance occur, they are apt to appear during the presentation of text information especially when there is greater demand on working memory or additional visual scanning requirements. As Risser et al. (2004) demonstrated, visual interference impaired performance when visual scanning requirements increased. This effect, however, is related more to structural interference than central processing interference because input modalities do not necessarily constitute the use of resources as defined by a limited capacity mechanism associated with physiological arousal (Wickens, 1991b). Nevertheless, the results validate a concern regarding the maintenance of speech and text information in working memory and their susceptibility to various sources of interference.

The Present Study

It appears that the nature of communication in the cockpit changes when the processing modalities change. Thus, it was necessary to investigate whether text presentation had the same limitations as speech throughout the entire communication process. More specifically, the receipt, acknowledgment, and execution of a message were evaluated with respect to processing speech and text and various sources of interference. One goal of the present study was to reexamine the effects of message format, interference type, and message length on task execution performance.

Another goal of this study was to investigate the response stage of processing. As noted previously in the ASRS reports, one class of problems associated with radio communications is pilot readback errors (Cardosi, 1993; Morrow, Lee, & Rodvold,

1993). With regard to ATC communications, this refers to the acknowledgement stage in the communication process. ATC issues instructions and the flight deck provides confirmation through some means of acknowledgement prior to execution. However, the acknowledgement response differs between a voice and datalink system. In a voice environment, the pilot acknowledges the message by repeating it (readback) prior to taking action. By contrast, datalink requires the pilot to acknowledge the text message with a manual keypress response via the CDU prior to its execution. As previously mentioned, a manual response with a keyboard or mouse is thought to require spatial resources (Wickens, 1991b). The previous studies by Risser and his colleagues (Risser et al., 2002; Risser et al., 2003, 2004; Scerbo et al., 2003) did not address the response stage of processing because there was no acknowledgement (or readback). For instance, Risser et al. (2002) required participants to recall words and write them down on paper. This could be considered a form of verbal response which could create interference with the verbal processing code used to maintain word lists in memory. Additionally, the CE task in all of the studies required a verbal response whereas both the verbal and visual tasks required a manual response. It could be argued that these differences at the response stage may have differentially affected performance. Thus, one objective of this study was to examine the nature of the acknowledgement response. Furthermore, during ATC communications, interference may be introduced before or after the acknowledgement response. Because an acknowledgement was not required in the previously mentioned series of studies, interference was present only during the receipt of the message prior to execution. In sum, a more comprehensive and ecologically valid examination of datalink must address the entire communication process and focus on the response modality of the

acknowledgement stage of communication as well as the timing of interference with respect to acknowledgement.

The present investigation addressed the interaction of processing stages and codes during the receipt, acknowledgement, and execution of ATC commands. Specifically, the effects of acknowledgement response and interference timing on command execution performance were studied during the communication process. Participants received different numbers of commands in both speech and text formats and were required to set controls in a flight simulator; however, they had to acknowledge the messages prior to execution. The acknowledgement required either a manual or verbal response and was counterbalanced across message format (see Figure 1).

In addition, the timing of interference was examined before and after the acknowledgment (see Figure 1). The interference tasks required CE or verbal resources. Unlike the previous series of studies, visual interference was not used in the present study because it appears to result from structural characteristics where there is a cost associated with visual scanning between two displays rather than central processing (Risser et al., 2004). The CE task required the participant to perform a fuel calculation. The verbal interference task required the participant to attend to the background radio chatter and respond to their aircraft call sign.

Acknowledgement Response. The different methods of responding to voice and datalink messages can be interpreted within the context of multiple-resource theory (Wickens, 1984, 1991b) and the working memory model (Baddeley & Hitch, 1974). According to multiple-resource theory, there should be less interference between the response stage of processing and the cognitive processing stage when different codes are

used. Specifically, a verbal response should share similar resources and interfere with verbal processing codes. Therefore, a verbal acknowledgement was expected to interfere with commands in working memory more than a manual acknowledgement.

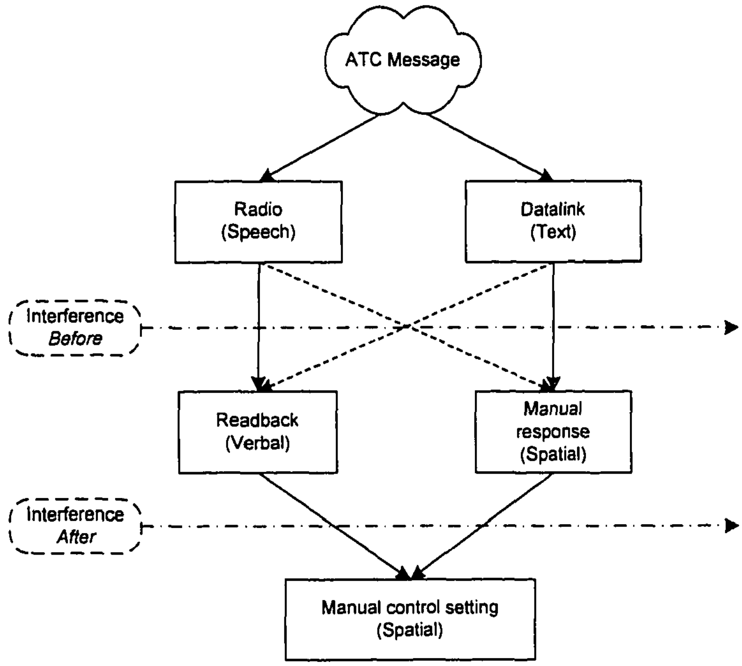

Figure 1. The interaction of acknowledgement response and interference timing for both speech and text message formats.

Although the working memory model does not make specific predictions related to the response stage of processing, the model does suggest that additional use of the phonological loop for a verbal acknowledgement could create interference with verbal information in memory. Furthermore, a verbal acknowledgement may have a larger negative impact on text than speech because text does not have direct access to the phonological loop. As previously mentioned, the phonological recoding of text makes it more susceptible to interference (Risser et al., 2002; Scerbo et al., 2003). Also, in another study, Schneider, Healy, and Barshi (2000) examined message length, wordiness,

and readback on the ability to execute commands. Participants were given procedural commands in both speech and text formats and were required to execute the commands by navigating a grid of squares. They found that readback performance was impaired more with redundant messages (e.g., "turn left two squares" versus "left two") and longer messages (e.g., more than two commands). Moreover, poorer performance was observed with text as compared to speech messages. They concluded that the negative impact of readback was related to verbal output interference. From a working memory model perspective, verbal output (readback) interfered with the commands in the phonological store. Additionally, the text format was negatively affected by redundancy and message length because an extra step in processing was required for the phonological recoding of visual-verbal information.

Schneider et al. (2000) demonstrated that readback itself can be a form of interference especially with longer text messages because of the phonological recoding of text. Therefore, verbal readback may not be appropriate for datalink. Instead, datalink should benefit from a manual response. However, Wickens (1984; 1991b) would argue that both speech and text utilize a verbal code. Thus, a manual acknowledgement response was expected to have less impact on performance than a verbal response regardless of the presentation format. Therefore, in the present study it was expected that a manual acknowledgement would result in better performance than a verbal acknowledgement because it does not require the use of the phonological loop and it does not share verbal resources with the commands maintained in the phonological loop.

Further, the acknowledgement response was expected to be differentially affected by interference. Multiple-resource theory would predict that a verbal acknowledgement

response would be negatively affected by verbal interference because they share similar processing codes. Similarly, the working memory model would also predict that verbal acknowledgement would be affected by verbal interference due to the unattended speech effect in the phonological loop. As previously described, unattended speech can interfere with other verbal information in memory. On the other hand, the working memory model would predict a greater negative impact on performance for CE over verbal interference as was demonstrated by Risser et al. (2002, 2003, 2004) and Scerbo et al. (2003). In the previously mentioned studies, the verbal and visual interference tasks were perceptual in nature and did not necessarily require information to be maintained in working memory. By contrast, in the present study the verbal interference task required participants to retain their aircraft call number in memory. Thus, it was expected that the verbal interference task would have a stronger effect than that observed by Risser et al. and Scerbo et al. However, CE interference was still expected to have a greater negative effect than verbal interference. Therefore, a verbal acknowledgement would result in poorer performance in the context of CE interference compared to verbal interference.

Interference Timing. The second goal of this study was to evaluate the effect of interference timing in the communication process. Specifically, two sources of interference were investigated: CE and verbal. According to the working memory model, CE processes utilize the most resources which in turn disrupts the rehearsal of information in memory regardless of processing code. The model also predicts that additional verbal processing would disrupt memory for verbal information already in the phonological loop as demonstrated by the unattended speech effect. Multiple-resource theory makes a more specific prediction regarding processing codes suggesting that

verbal interference would have a negative effect on performance regardless of modality because both speech and text utilize a verbal processing code (Risser et al., 2002, 2003, 2004; Scerbo et al., 2003). Therefore, CE interference was expected to have the greatest negative effect on command execution performance followed by verbal interference. Previous studies have demonstrated that interference during the receipt of a message can impair both recall and execution performance and this finding was consistent with both a verbal (written) response (Risser et al., 2002) and a manual (mouse movement) response (Risser et al., 2003, 2004; Scerbo et al., 2003).

As discussed in the previous section, acknowledgement differs between voice and datalink communication because each system uses a different method of responding. Although communication protocol requires an immediate response from the pilot to ATC requests, the time taken to respond with datalink may be longer and more variable than with radio communication. In the voice environment, communication occurs in real time between the sender and the receiver (similar to a telephone conversation). As a message is being sent, it is simultaneously being received. Therefore, there are fewer opportunities for time delays in a voice transaction. On the other hand, in the datalink environment, once a message is received, the pilot must navigate display menus in the CDU to view the message. After the message is read, it must be acknowledged by interacting with the CDU again before executing the request. Thus, with datalink there is a delay between the time a message is first read and when it is acknowledged and another delay between the time the message is acknowledged and the request is executed.

The time delays inherent in datalink may make it more susceptible to sources of interference during the communication process. Studies have demonstrated that flight

crews often begin making navigational changes to the aircraft (manually or through the autopilot) before they acknowledge the message (Rehmann & Mogford, 1996; Van Gent, 1995). This deviation from procedure may be an attempt to reduce the time gap between the receipt and execution of a message. Thus, datalink seems to be at most risk for interference because responses are not immediate. Further, as a result of time delays in datalink communication, an attentional shift from the primary task may occur and resources may be temporarily reallocated to a secondary task (e.g., task switching).

Accordingly, another goal of the present study was to examine the effect of interference before and after acknowledgement on command execution performance. In fact, pilots may use sources of interference intentionally to ensure compliance and safety with an ATC request. For example, Lozito, McGann, and Corker (1993) found that pilots were more likely to carry out other tasks between the receipt and response to ATC communications over datalink as compared to radio. The authors suggested that pilots utilize the time delays to their advantage to distribute their workload. For instance, after a datalink message is read by the flight crew, the pilot may briefly attend to radio chatter before acknowledging the message or the pilot may acknowledge the message and then may decide to carry out some other activity prior to executing the request. In the first example, the pilot would have to code the ATC message information in memory, switch to a completely different task using a similar processing code (radio chatter), then switch back to the original task and recall the information to acknowledge the message. In the second example, after the pilot coded the information in memory and acknowledged the message, the pilot would have to switch to a second task prior to execution. Thus, the first example would require more task switching because the interference occurred prior

to acknowledgement.

Because interacting with a datalink system causes time delays in the communication process, it also creates a task switching environment in which multiple tasks must be processed in sequence. Although Wickens does not specifically address task switching in his multiple-resource theory, he does suggest that task interference can occur when one must switch between two tasks involving cognitive programs that share similar processing codes (Wickens, 1991b). Similarly, retroactive interference can be reduced if two sources of information are coded to use different working memory components (Haelbig, Mecklinger, Schriefers, & Friederici, 1998). It has also been argued that attentional resources are needed to control task switching (Baddeley et al., 2001). Given these notions, in the present study it was expected that when interference occurs prior to acknowledgement it would result in more task switching than when it occurs after acknowledgement and therefore provide less opportunity and resources for rehearsal. Thus, interference prior to acknowledgement was expected to result in poorer performance than interference introduced after acknowledgement because the additional task switching would require more resources. Further, verbal responses were expected to be more susceptible to the negative effects of interference prior to acknowledgement than manual responses. In this case, verbal responses share a similar verbal processing code with commands in memory and more resources will be required when switching from an interference task to verbal acknowledgement where commands must be recalled. On the other hand, the working memory model predicts that interference will disrupt performance regardless of timing because both verbal and CE sources of interference will disrupt rehearsal of commands in the phonological loop. However, as previously

discussed, both CE resources and the phonological loop (through the verbal control of executive processes) have been implicated in task switching (Baddeley et al., 2001; Baddeley, 2002). Therefore, because both CE and verbal resources are used in the control of task switching, both were expected to have equal and negative effects on execution performance when presented prior to a verbal acknowledgement.

Consistent with the limitations of the phonological loop as demonstrated by the word length effect in the working memory model, memory for ATC instructions will become degraded when messages are too long or complex (Cardosi, 1993). Optimal performance with natural speech ATC communications was shown to be limited to no more than three topics in a message (Barshi, 1997). Using tape recordings from terminal operations, Morrow et al., (1993) demonstrated that readback errors were also more frequent when there was more than one command. In fact, 57% of incorrect readbacks were the result of the pilots substituting a digit from another command into the incorrectly repeated command. The authors noted that interference between commands increased as working memory load increased. Furthermore, Risser et al. (2004) and Scerbo et al. (2003) showed that increasing the number of commands reduced performance differences between the sources of interference as capacity became depleted. Therefore, increasing the number of commands in the present study was expected to result in greater performance impairments and these effects were to be compounded by interference. However, as the number of commands increase, it was expected that the magnitude of the differences between the sources of interference would become smaller as demonstrated previously by Scerbo et al. (2003).

METHOD AND PROCEDURE

Participants

Thirty-two graduate students from ODU participated in this experiment and were paid $30 each. There were 14 male and 18 female participants whose ages ranged from 22 to 39 ($M = 26.6$). All reported normal or corrected vision and no auditory deficits. They were all native speakers of English.

Apparatus

Flight simulator. X-Plane flight simulator version 7.30 (X-Plane, 2003) was used as the cockpit display and for control manipulation. The cockpit display simulated a Boeing 777-200 cockpit. Participants were required to manipulate the heading, speed, and altitude controls on the mode control panel using the mouse as shown in Figure 2. The simulator ran on a 1.7 GHz Pentium 4 PC with a single 18 in flat panel display set at a 1024x768 resolution and 32 bit color depth. Auditory information was presented through two desktop speakers and a subwoofer.

CDU. A simulated CDU was created and presented on a 1.5 GHz Pentium-M laptop with a 12 in display also set at a 1024x768 resolution and 32 bit color depth. The CDU was designed with moderate fidelity and incorporated relevant menu systems and working buttons to handle incoming messages as shown in Figure 3. It was controlled using the mouse. In the present study, messages were restricted to one screen. The datalink SELCAL (selective calling) chime was played when there was a new text message. This is the same chime played in an actual aircraft. The datalink chime was a 700 ms sound file recorded in stereo at a 44 KHz sample rate and 16-bit depth with an average frequency of 573 Hz.

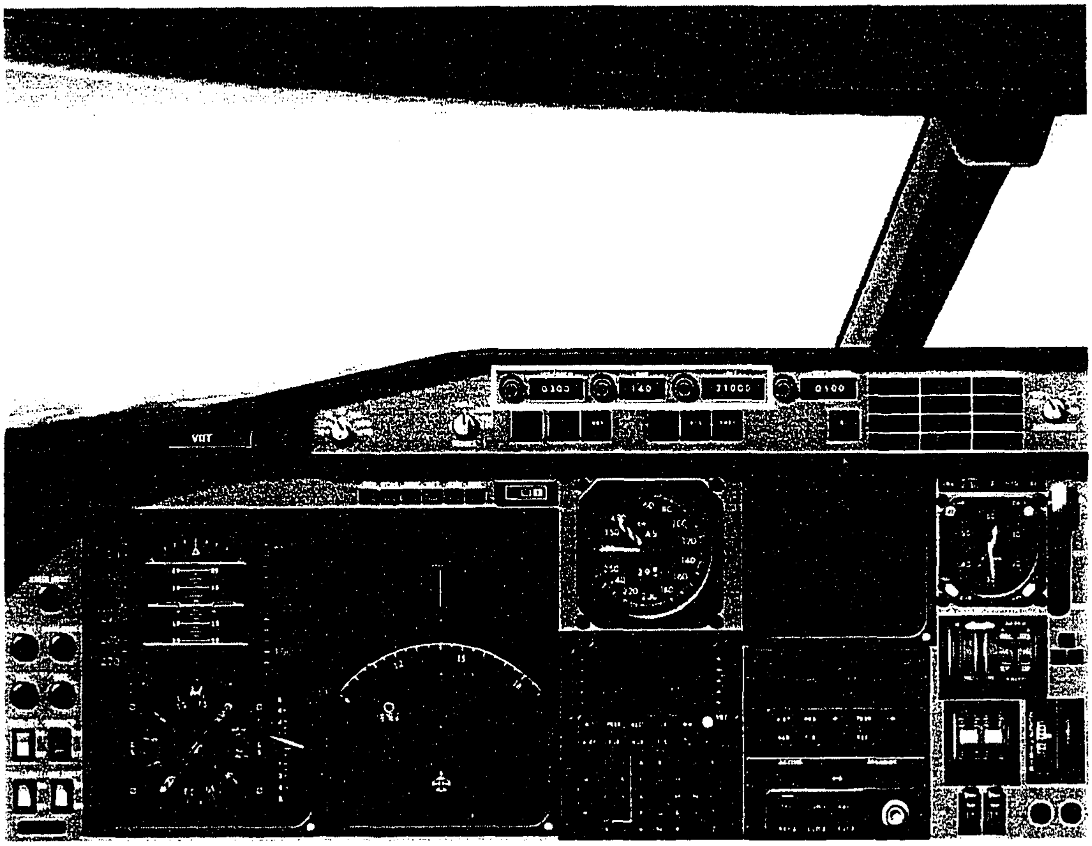

Figure 2. The X-Plane cockpit. Controls to manipulate speed, heading, and altitude are highlighted in the bold white box on the mode control panel.

The flight simulator and the CDU computers were connected via a 100Mb network switch. Information was exchanged between the two computers via a UDP network protocol.

Stimuli

Commands. Simulated ATC commands were presented as both speech and text and are presented in Appendix A. In both message formats, commands were presented as complete three-word phrases in a verb-object-indirect object syntax (e.g., change heading 180). Speech messages were recorded monophonically at 22 KHz and 16-bit depth in a

male voice using prosodic speech. They were presented at a normal conversational level of approximately 60 dBC measured from the sitting distance of the participant.

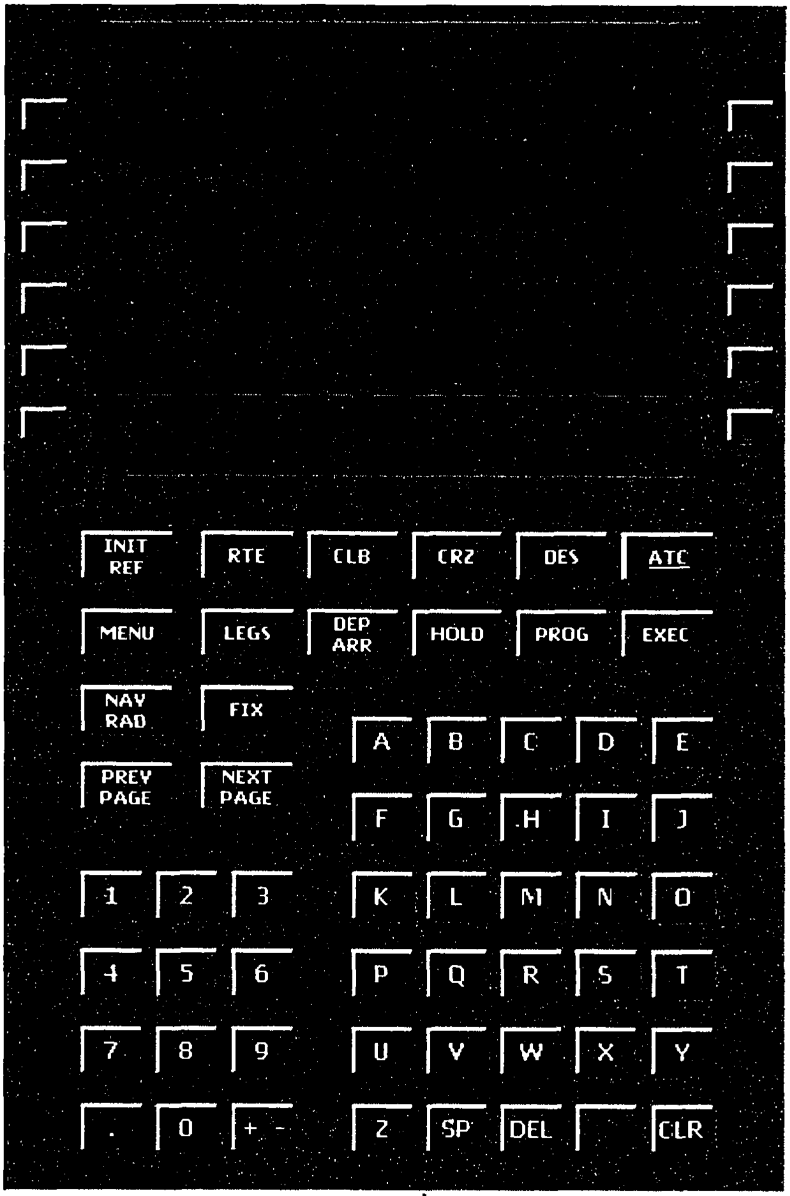

Figure 3. The CDU used to display and respond to incoming text (datalink) messages.

There was a 750 ms ISI between commands when more than one speech command was presented. Text messages were presented on the simulated CDU screen.

The text was displayed in a green 14-point Arial font on a black background. To equate the stimulus presentation times between speech and text messages, a text message was displayed for the median length of time of a speech message with the same number of commands. Therefore, text messages were displayed 2.5 s for 1-command messages, 5 s for 2-command messages, and 7.5 s for 3-command messages.

Interference tasks. The interference tasks were selected based on their relevance to components of working memory and their application to the flight deck. Of 29 aviation tasks, calculating fuel and ATC communication were both ranked as high priority tasks during the cruise phase of flight (Schvaneveldt, Beringer, & Lamonica, 2001).

Two interference tasks were used. The verbal interference task replicated the background radio chatter that is continually present in an actual cockpit. Participants were required to listen and identify their aircraft call sign and respond by pressing the spacebar on the keyboard. As a cue, an instruction was presented on the laptop at the beginning of the verbal interference task and remained on the screen for the duration of the task: "Respond to CALLSIGN by pressing SPACEBAR". The call signs were recorded monophonically at 22 KHz and 16-bit depth in a male voice that was different from the speech commands. Each call sign included a single digit number and a phonetic letter (e.g., "Alpha-Four") as shown in Appendix B. Each call sign had an average duration of 900 ms with an interstimulus interval (ISI) of 1000 ms. For each trial, there was a total of seven stimuli containing three targets and four distractors. The ratio of targets to distractors was selected to produce a moderate level of task demand as demonstrated by Casali and Wierwille (1983). Targets and distractors were presented

randomly with the restriction that no two targets be presented in succession. Furthermore, the distractors included call numbers that were both similar and dissimilar to the participants' call number. For example, if the target call sign was "Alpha-Four" a similar distractor was "Alpha-Eight" or "Echo-Four". A dissimilar distractor was "November-Six." Of the four distractors, three were similar and one was dissimilar. There was a different call sign assigned to each experimental session. The call sign for the first experimental session was "Alpha-Four" and "Delta-Eight" was the call sign for the second experimental session. The total time required to complete the verbal interference task was approximately 14 s.

The second source of interference was a CE task requiring participants to calculate simple fuel algorithms with values rounded to the nearest thousandth to facilitate the mental arithmetic. The fuel status display in the simulator showed the total fuel remaining (Fuel Tot) in pounds and the fuel flow (FF) in pounds per hour (pph) for each engine and (see Figure 4).

Figure 4. Fuel status display showing total fuel and fuel flow for each engine. The bottom three values display the length of time the aircraft can fly, the distance the aircraft can fly, and the total weight of the aircraft.

Participants had to answer the question, "At the current fuel burn, how much total fuel will remain after one more hour?" The answer was obtained by solving the following equation: Total fuel – ($FF_1 + FF_2$). For example, given the values shown in Figure 4, the answer is 128,000 lbs of fuel or 150,000 – (11,000 + 11,000). Participants were required to perform the calculation in their heads without pencil and paper or calculator. The fuel values were captured from the simulator and displayed on the secondary display (e.g., laptop) because the values in the X-Plane fuel display changed continuously in real time. Participants responded by entering their final value into a blank entry form on the laptop computer and then used the mouse to click on a "Done" icon displayed on the laptop screen when finished. To ensure a comparable time with the verbal interference task (14 s), additional fuel calculation questions were presented. Immediately after entering the value for the first question, the fuel values remained on the screen, and the next question was displayed: "At the current fuel burn, how much total fuel will remain after two more hours?" The answer was obtained by solving the following equation: Total fuel – (($FF_1 + FF_2$)*2). After participants answered the second question if time permitted, a third question was displayed: "At the current fuel burn, how much total fuel will remain after three more hours?" The answer was obtained by solving the following equation: Total fuel – (($FF_1 + FF_2$)*3). Participants responded to the second and third questions in the same manner as the first.

The responses to the verbal and CE interference tasks were manual key presses on the keyboard to minimize any additional interference potentially caused by a verbal response. Additionally, both interference tasks were cued by a distinct 500 ms 500 Hz tone (one that is separate from the datalink chime). The tone was recorded

monophonically at a 22 KHz sample rate and 16-bit depth.

Last, a control condition was included in which there was no secondary task. In this case, there was no time delay prior to or after acknowledgement. Therefore, participants immediately acknowledged a message and executed the commands.

Design

The experiment used a full factorial within-subjects 2 x 2 x 3 x 3 x 2 x 2 design that included message format (speech, text), interference type (verbal, CE), message length (1, 2, 3), interference timing (before acknowledgement, after acknowledgement, and none), acknowledgement response (verbal, manual), and experimental block (first, second).

The experimental flight consisted of a series of trials. Each trial included a factorial combination of message format, interference type, interference timing, acknowledgement response, and message length. There were two experimental blocks with 72 trials per block or 144 total trials. Each message format was presented on a separate experimental session and the order of sessions was counterbalanced across participants. Within each level of interference task, participants performed both levels of response acknowledgement with the order of interference timing and message length presented randomly, but counterbalanced across trials. Interference timing was blocked and presented randomly within each level of response acknowledgement. Interference task and acknowledgement response were counterbalanced between participants. Each participant performed the same order of interference task and acknowledgement response for both experimental sessions (i.e., speech and text). See Appendix C for the complete counterbalanced conditions.

The primary dependent measures were the proportion of controls correctly set in the correct order (CSCO), the proportion of controls correctly set (CS), and the proportion of correct responses to the verbal and CE interference tasks. Additional measures included the number of incorrect controls set, the proportion of attempted questions on the CE task, the errors of commission during the verbal interference task, and response time (RT). The errors of commission were defined as a participant's response to nontarget stimuli for the verbal interference task. Response time was calculated for a complete trial starting after the presentation of the commands and ending after the controls have been set.

Procedure

Participants completed two experimental sessions within 48 hours. The experiment was conducted in a sound attenuated booth. After participants read and signed the consent form they were seated in front of the flight simulator and CDU displays. The flight simulator screen was elevated approximately 8 in so the CDU screen could be placed directly in front of it. Participants completed a training session before each experimental session. The training and experiment began with the autopilot turned on and the plane in straight and level flight at 20,000 ft.

Training. The training was divided into six modules: message presentation, acknowledgement response, flight simulator controls, verbal interference task, CE interference task, and timing of interference. The first module allowed participants to become familiar with the two presentation formats and varying message lengths. Next, they were instructed how to perform verbal readbacks and manual responses using a "Response Send" button on the CDU. The third module addressed the flight simulator

controls and how to manipulate them. In the third and fourth modules, participants were trained to perform the verbal and CE interference tasks. They practiced both interference tasks until they reached 100% accuracy in two consecutive trials. Last, they completed several practice trials that included the timing of interference tasks, as well as acknowledging the message, performing the interference tasks, and manipulating the controls. The training session took approximately 25 min.

Experiment. Instructions regarding the interference type and acknowledgement response were displayed on the secondary display at the beginning of a set of trials for each level of response (i.e., every nine trials). Participants were presented with one, two, or three commands that required an acknowledgement response which alternated with an interference task when present. Participants were instructed to manually execute the commands by correctly setting the simulator controls in the correct order. Figure 5 shows a timeline of the procedure with interference present.

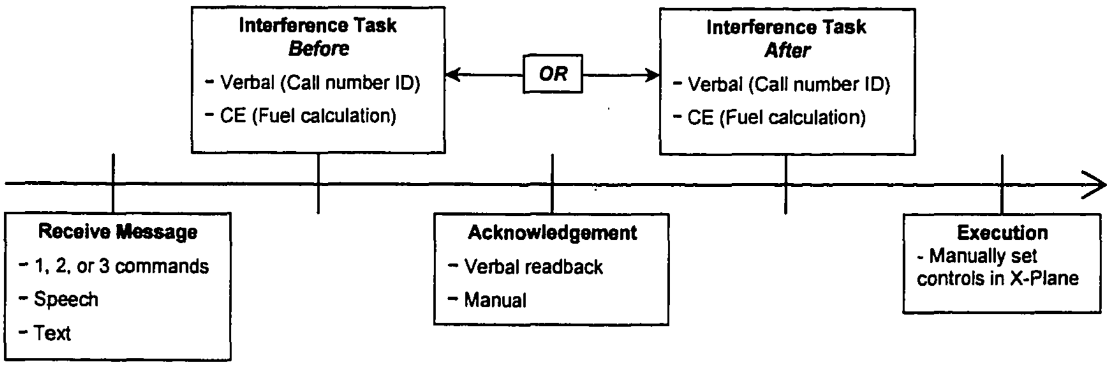

Figure 5. A timeline of the procedure for each trial when interference was present.

Participants heard the commands in the speech condition. In the text condition, a chime sounded and the commands were displayed on the CDU. Participants were required to acknowledge messages either verbally or manually. They immediately saw a

message displayed on the laptop that read, "READBACK commands then press SPACEBAR". Verbal acknowledgement required participants to readback the commands and press the spacebar on the keyboard when finished (similar to keying the microphone in a cockpit). This step was confirmed by the experimenter. In the manual acknowledgement condition, a "Response Send" message was displayed in the CDU immediately after the commands were presented. The manual acknowledgement required participants to respond by pressing a button on the CDU next to the "Response Send" message. Although a manual keypress on keyboard was required at the end of the verbal acknowledgement, it required fewer manual/spatial resources as compared to pressing the "Response Send" button on the CDU with a manual acknowledgement. The manual acknowledgment required a search for a target (i.e., the button on the CDU) and the acquisition of that target with the mouse (i.e., moving the mouse over the button and clicking on it). Interference tasks were presented 1000 ms after the commands and prior to acknowledgement or 1000 ms after acknowledgement and prior to execution. Acknowledgement screens were presented for 3.5 s for a 1-command message, 6 s for a 2-command message, and 8.5 s for a 3-command message. Note that each acknowledgement screen was displayed 1 s longer than the median presentation time of the commands for each command length. The additional time was provided to acquire the "Response Send" button with the mouse in the manual acknowledgement condition. In the verbal acknowledgement condition, participants read the acknowledgement screen and responded with a verbal readback of the commands. After acknowledgement and completing the interference task, participants saw a screen displayed on the laptop with the message, "Set CONTROLS and press DONE". After setting the controls on the

simulator display, they clicked on a "Done" icon displayed on the laptop. There was a 2 s delay before the next trial began. The time to complete one experimental session was approximately 1 hour and 25 minutes. The total time to complete the entire experiment was approximately 2 hours and 50 minutes. After completing the second experimental session, participants completed a strategy questionnaire (see Appendix D) to determine how much verbal processing was involved with the CE interference task. Upon completion of the experiment, participants were debriefed.

RESULTS

Data Analyses

The data were analyzed using a repeated-measures ANOVA with an alpha level of .05 for statistical significance. Tukey post hoc comparisons were used to analyze significant differences among means. Partial Eta squared was used to measure effect sizes. When necessary, data were converted to proportions prior to analysis. Experimental block and session were analyzed separately for practice effects. Of note, the independent variable, interference timing, included one level in which no interference was presented as "none" to serve as the control condition. Therefore, references are made to the control condition of interference timing in the following analyses.

Preliminary Analyses

A preliminary analysis of the data was performed on the main dependent variables to determine if there were practice effects using a 2 (block) x 2 (session) ANOVA for the proportion of correctly set controls in the correct order (CSCO) and the proportion of controls correctly set (CS). The results showed no main effect for experimental block, but there was a main effect for session, $F(1, 31) = 15.03, p < .000, MSE = 0.251, \eta p^2 = .005$. There was a lower proportion of CSCO in the first session ($M = .600, SD = .434$) compared to the second session ($M = .657, SD = .411$). The Block x Session interaction was also significant, $F(1, 31) = 4.24, p = .048, MSE = .066, \eta p^2 = .0003$. There was a lower proportion of CSCO in Block 1 within Session 1 ($M = .584, SD = .436$) compared to Block 2 within Session 1 ($M = .615, SD = .430$), Block 1 within Session 2 ($M = .657, SD = .411$), and Block 2 within Session 2 ($M = .657, SD = .411$). Both of the blocks in Session 2 also differed from Block 2 in Session 1.

For the CS measure, again the main effect for block was not significant but the main effect for session was significant, $F(1, 31) = 15.00$, $p < .000$, $MSE = .189$, $\eta p^2 = .004$. There was a lower proportion of CS in the first session ($M = .662$, $SD = .398$) compared to the second session ($M = .712$, $SD = .368$). There was no significant Block x Session interaction.

Separate 3-way ANOVAs were performed on the CSCO measure for block and session with each of the other 5 independent variables to determine if block or session interacted with another variable. Results demonstrated that the effect of block did not interact with any other variables. However, there was a significant Session x Length interaction, $F(2, 62) = 3.81$, $p = .027$, $MSE = .181$, $\eta p^2 = .003$. Means and standard deviations for 1, 2, and 3 commands in Session 1 were .876 ($SD = .329$), .600 ($SD = .433$), and .324 ($SD = .340$), respectively. In Session 2, the means and standard deviations for 1, 2, and 3 commands were .900 ($SD = .301$), .704 ($SD = .398$), and .368, ($SD = .335$), respectively. The results also show that there were no differences between Sessions 1 and 2 when there was only one command, but that there was better performance in Session 2 with longer messages (i.e., 2 and 3 commands).

Controls Correctly Set in Correct Order

The results of a 2 (format) x 2 (interference) x 2 (response) x 3 (timing) x 3 (length) ANOVA performed on the proportion of CSCO are shown in Table 2. There was a main effect of interference timing, $F(2, 62) = 77.970$, such that there was a lower proportion of CSCO when interference was presented before acknowledgement ($M = .545$, $SD = .432$) compared to after acknowledgement ($M = .596$, $SD = .435$). In the control condition (i.e., no interference), there was a significantly greater proportion of

CSCO (*M* = .746, *SD* = .373) compared to both before and after timing conditions. The main effect of length, $F(2, 62) = 438.040$, demonstrated that there was a lower proportion of CSCO as message length increased. All message lengths differed significantly from one another. The means and standard deviations for 1-, 2-, and 3-command messages were .888 (*SD* = .315), .652 (*SD* = .419), and .346 (*SD* = .338), respectively.

Table 2
Analysis of Variance for the Proportion of CSCO

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
Format (F)	1	0.568	0.568	1.600	0.215	0.002
Timing (T)	2	33.484	16.742	77.970	<.0001*	0.128
Length (L)	2	226.985	113.493	438.040	<.0001*	0.500
Interference (I)	1	11.068	11.068	39.000	<.0001*	0.046
Response (R)	1	5.027	5.027	53.220	<.0001*	0.022
F x T	2	1.265	0.632	5.840	0.005*	0.006
F x L	2	3.486	1.743	11.840	<.0001*	0.015
F x I	1	1.765	1.765	13.240	0.001*	0.008
F x R	1	0.483	0.483	6.400	0.017*	0.002
T x L	4	4.205	1.051	8.660	<.0001*	0.018
T x I	2	4.715	2.358	15.810	<.0001*	0.020
T x R	2	0.755	0.378	2.890	0.063	0.003
L x I	2	0.876	0.438	3.090	0.053	0.004
L x R	2	3.071	1.536	10.210	0.0001*	0.013
I x R	1	0.006	0.006	0.040	0.840	0.000
F x T x L	4	0.630	0.158	1.840	0.126	0.003
F x T x I	2	0.604	0.302	3.060	0.054	0.003
F x T x R	2	0.247	0.124	1.430	0.248	0.001
F x L x I	2	0.756	0.378	3.060	0.054	0.003
F x L x R	2	1.816	0.908	9.000	0.0004*	0.008
F x I x R	1	0.180	0.180	2.090	0.158	0.001
T x L x I	4	1.107	0.277	3.410	0.011*	0.005
T x L x R	4	0.720	0.180	2.180	0.075	0.003
T x I x R	2	0.626	0.313	4.020	0.023*	0.003
L x I x R	2	0.129	0.065	0.770	0.467	0.001
F x T x L x I	4	0.512	0.128	1.600	0.180	0.002
F x T x L x R	4	0.672	0.168	2.100	0.084	0.003
F x T x I x R	2	0.948	0.474	3.960	0.024*	0.004
F x L x I x R	2	0.225	0.113	1.240	0.297	0.001
T x L x I x R	4	0.359	0.090	0.910	0.463	0.002

Table 2 (Continued)

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
F x T x L x I x R	4	0.181	0.045	0.500	0.735	0.001
Subject (S)	31	35.608	1.149			
F x S	31	10.983	0.354			
T x S	62	13.312	0.215			
L x S	62	16.064	0.259			
I x S	31	8.798	0.284			
R x S	31	2.928	0.094			
F x T x S	62	6.713	0.108			
F x L x S	62	9.123	0.147			
F x I x S	31	4.134	0.133			
F x R x S	31	2.338	0.075			
T x L x S	124	15.050	0.121			
T x I x S	62	9.248	0.149			
T x R x S	62	8.104	0.131			
L x I x S	62	8.777	0.142			
L x R x S	62	9.328	0.150			
I x R x S	31	4.297	0.139			
F x T x L x S	124	10.634	0.086			
F x T x I x S	62	6.105	0.098			
F x T x R x S	62	5.371	0.087			
F x L x I x S	62	7.644	0.123			
F x L x R x S	62	6.251	0.101			
F x I x R x S	31	2.670	0.086			
T x L x I x S	124	10.078	0.081			
T x L x R x S	124	10.233	0.083			
T x I x R x S	62	4.820	0.078			
L x I x R x S	62	5.205	0.084			
F x T x L x I x S	124	9.947	0.080			
F x T x L x R x S	124	9.908	0.080			
F x T x I x R x S	62	7.421	0.120			
F x L x I x R x S	62	5.636	0.091			
T x L x I x R x S	124	12.287	0.099			
F x T x L x I x R x S	124	11.167	0.090			

There was also a main effect of interference type, $F(1, 31) = 39.000$, where there was a lower proportion of CSCO for the CE task ($M = .580$, $SD = .437$) as compared to the verbal task ($M = .678$, $SD = .403$). The main effect of response, $F(1, 31) = 53.220$, demonstrated that there was a lower proportion of CSCO with a verbal acknowledgement

($M = .596$, $SD = .427$) compared to a manual acknowledgement ($M = .662$, $SD = .416$).

In addition to the main effects, there were several significant interactions. Presentation format interacted with interference timing, $F(2, 62) = 5.840$, message length $F(2, 62) = 11.840$, interference type, $F(1, 31) = 13.240$, and acknowledgement response, $F(1, 31) = 6.400$. Additionally, interference timing interacted with message length, $F(4, 124) = 8.660$ and interference type, $F(2, 62) = 15.810$. Message length also interacted with acknowledgement response, $F(2, 62) = 10.210$. Furthermore, there was a 3-way interaction among format, message length, and acknowledgement response, $F(2, 62) = 9.000$. The nature of this interaction is shown in Figure 6.

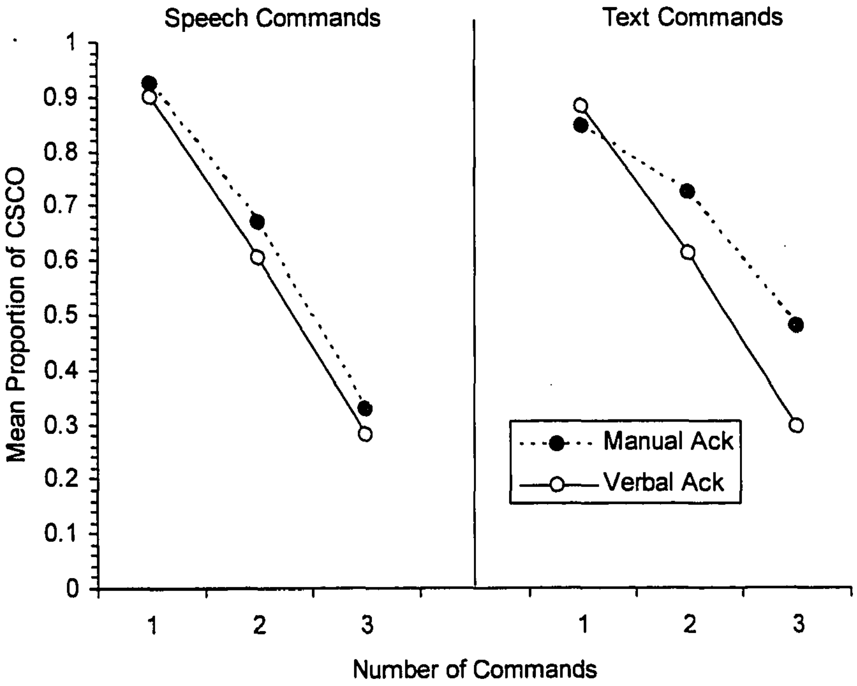

Figure 6. Mean proportion of CSCO for the interaction among format, message length, and acknowledgement response. Manual and verbal acknowledgement responses are plotted for each message length. The effects for speech are presented on the left and the effects for text are presented on the right.

A comparison of the means demonstrated a clear effect of message length where

there was a lower proportion of CSCO with an increase in the number of commands. Each command length differed from the others for both manual and verbal acknowledgements. In the speech condition, there were no differences between response types at each message length. Within the text condition, however, the proportion of CSCO with a verbal acknowledgement was lower than with a manual acknowledgement at two and three commands. Comparing acknowledgement responses between formats, there were no differences in CSCO between speech and text formats with a verbal acknowledgement at the same command length. However, there was a lower proportion of CSCO in the text as compared to the speech condition with a manual acknowledgement and one command. On the other hand, there was a lower proportion of CSCO with three commands and a manual acknowledgement in the speech as opposed to text condition. There were no differences between response types between the speech and text formats with two commands.

A significant interaction was also observed among interference timing, message length, and interference type, $F(4, 124) = 3.410$, and this is shown in Figure 7. A comparison of the means demonstrated that once again, length had an increasingly negative effect on CSCO as the number of commands increased. Each command length differed from one another within verbal interference, CE interference, and the control condition. In both before and after interference timing conditions, there was a lower proportion of CSCO with CE interference compared to verbal interference at one and two commands, but there was no difference at three commands. As expected, there were no differences in CSCO between interference types within the control condition.

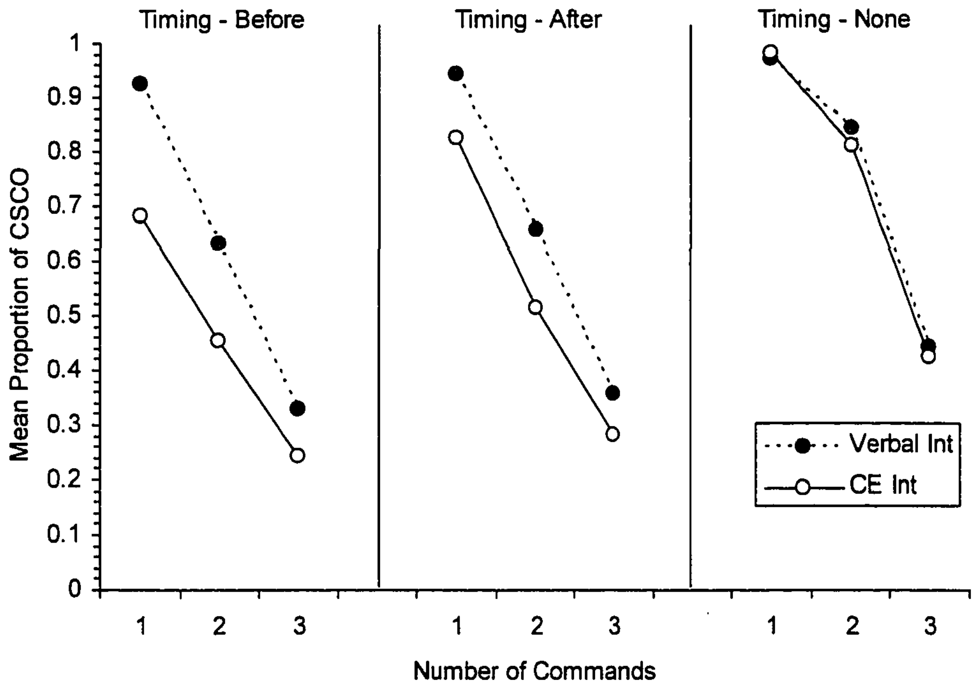

Figure 7. Mean proportion of CSCO for the interaction among interference timing, message length, and interference type. Verbal and CE interference are plotted for each message length. Before, after, and no interference timing conditions are shown from left to right.

Between before and after timing conditions there were no differences for verbal interference at each message length. Compared to the control condition, both before and after timing conditions resulted in a lower proportion of CSCO with two commands. However, when there were three commands, there was a lower proportion of CSCO in the before condition with verbal interference compared to the control condition.

In contrast to verbal interference, CE interference differed between before and after timing conditions. There was a lower proportion of CSCO with one command before acknowledgement compared to after acknowledgement. However, there were no differences with CE interference before and after acknowledgement with two and three commands. Furthermore, CE interference presented both before and after

acknowledgement at all three command lengths resulted in a lower proportion of CSCO when compared to the control condition at the same command lengths.

There was also a significant 3-way interaction among interference timing, interference type, and acknowledgement response, $F(2, 62) = 4.020$, as well as a significant 4-way interaction among format, interference timing, interference type, and acknowledgement response, $F(2, 62) = 3.960$. The 4-way interaction is shown in Figure 8.

Regarding the speech condition, a comparison of the means demonstrated that there were no differences between manual and verbal acknowledgements in the before interference timing condition with both verbal and CE interference. In the after timing condition, there were also no differences between manual and verbal acknowledgement with both verbal and CE interference. Within before and after timing conditions, there were no differences between types of interference. As expected, there were no differences between manual and verbal acknowledgement responses in the control condition.

Across timing conditions, a manual acknowledgement with verbal interference did not differ between before and after timing conditions. The same was true for a manual acknowledgement and CE interference between before and after timing conditions. However, both timing conditions resulted in a lower proportion of CSCO than in the control condition. On the other hand, a verbal acknowledgement with verbal interference did not differ between before and after timing conditions or from the control. A verbal acknowledgement with CE interference did not differ between before and after

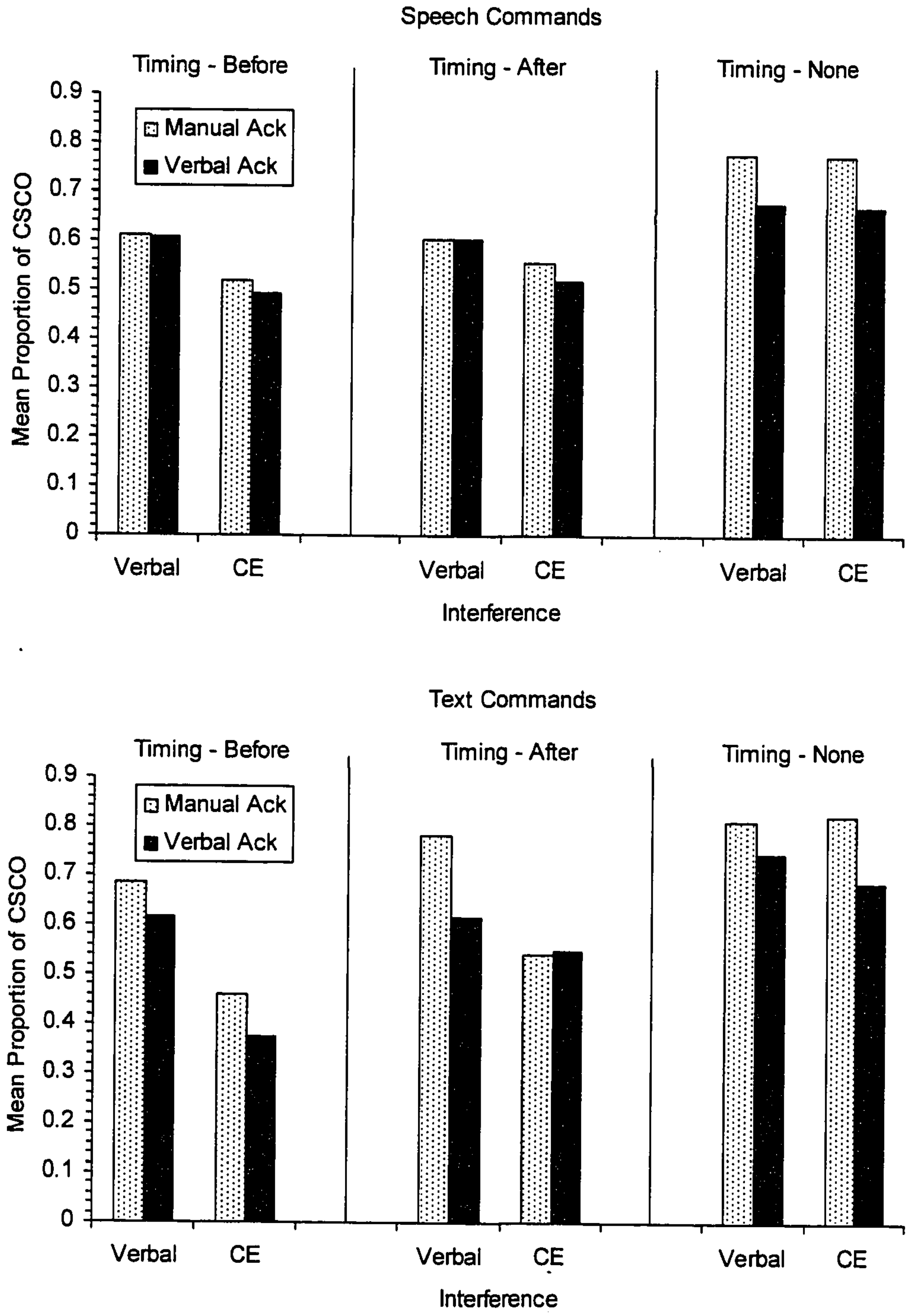

Figure 8. Mean proportion of CSCO for the interaction among format, interference timing, interference type, and acknowledgement response. Manual and verbal acknowledgement responses are plotted for each type of interference and timing. Before, after, and no interference timing conditions are presented from left to right. The effects for speech are presented on top and the effects for text are presented on the bottom.

than in the control condition.

In the text condition, there were no differences between a manual and verbal acknowledgement in the before timing condition within both verbal and CE interference. However, there was a lower proportion of CSCO with either type of acknowledgement in the CE as compared to verbal interference task. In the after timing condition, there was a lower proportion of CSCO with a verbal acknowledgement compared to a manual acknowledgement when there was verbal interference. In contrast, there were no differences between acknowledgements in the after timing condition with CE interference. In the after timing condition, there also was a lower proportion of CSCO with a manual acknowledgement and CE interference compared to verbal interference. Additionally, there were no differences with a verbal acknowledgement between types of interference in the after timing condition. In the control condition, there were no differences between manual and verbal acknowledgements within verbal interference trials; however, a verbal acknowledgement resulted in a lower proportion of CSCO compared to manual acknowledgement within the CE interference trials.

Across timing conditions, a manual acknowledgement with verbal interference did not differ among any of the timing conditions. A manual acknowledgement with CE interference did not differ between before and after timing conditions, but both timing conditions differed from the control condition. Also, a verbal acknowledgement with verbal interference did not differ among any of the timing conditions. On the other hand, a verbal acknowledgement with CE interference resulted in a lower proportion of CSCO in the before timing condition as compared to the after timing condition. Both before and after timing conditions with a verbal acknowledgement and CE interference resulted in a

lower proportion of CSCO as compared to the control condition.

A comparison of speech and text demonstrated that there were no differences among means in the before timing or control conditions. However, speech and text did differ in the after timing condition. In speech as compared to text, there was a lower proportion of CSCO in the after timing condition with a manual acknowledgement and verbal interference.

Controls Correctly Set

The CSCO measure requires participants to not only set the controls correctly, but also in the correct order. The CS measure addresses the number of controls correctly set regardless of order and is therefore less stringent. A 2 (format) x 2 (interference) x 2 (response) x 3 (timing) x 3 (length) ANOVA was performed on the CS measure and the results are reported in Table 3. There was a main effect of format, $F(1, 31) = 9.010$, where there was a lower proportion of CS when messages were presented as speech (M = .667, SD = .386) compared to text (M = .708, SD = .382). An effect of interference timing, $F(2, 62) = 100.470$, demonstrated a lower proportion of CS when interference was presented before acknowledgement (M = .601, SD = .407) as compared to after acknowledgement (M = .660, SD = .396). In the control condition (M = .801, SD = .317) there was a greater proportion of CS compared to both before and after timing conditions. There was also a main effect of length, $F(2, 62) = 357.460$, where there was a lower proportion of CS as message length increased. All message lengths differed significantly from one another. In order, the means and standard deviations for 1-, 2-, and 3-command messages were .896 (SD = .311), .714 (SD = .378), and .452 (SD = .323), respectively. Also, an effect of interference type, $F(1, 31) = 39.860$, demonstrated a lower proportion

of CS under CE interference (M = .641, SD = .402) as compared to verbal interference (M = .734, SD = .360). In addition, there was an effect of response, $F(1, 31) = 47.300$, where there was a lower proportion of CS when a verbal acknowledgement was required (M = .653, SD = .393) as compared to a manual acknowledgement (M = .722, SD = .373).

Table 3

Analysis of Variance for the Proportion of CS

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
Format (F)	1	1.960	1.960	9.010	0.005*	0.010
Timing (T)	2	32.387	16.193	100.470	<.0001*	0.141
Length (L)	2	152.978	76.489	357.460	<.0001*	0.436
Interference (I)	1	9.755	9.755	39.860	<.0001*	0.047
Response (R)	1	5.489	5.489	47.300	<.0001*	0.027
F x T	2	1.336	0.668	4.860	0.011*	0.007
F x L	2	5.212	2.606	31.050	<.0001*	0.026
F x I	1	2.014	2.014	18.630	0.0002*	0.010
F x R	1	0.087	0.087	0.990	0.327	0.000
T x L	4	3.405	0.851	8.600	<.0001*	0.017
T x I	2	3.426	1.713	13.080	<.0001*	0.017
T x R	2	1.155	0.578	5.070	0.009*	0.006
L x I	2	1.146	0.573	6.140	0.004*	0.006
L x R	2	3.758	1.879	16.360	<.0001*	0.019
I x R	1	0.015	0.015	0.210	0.646	0.000
F x T x L	4	0.286	0.072	0.860	0.489	0.001
F x T x I	2	0.580	0.290	4.070	0.022*	0.003
F x T x R	2	0.204	0.102	1.020	0.367	0.001
F x L x I	2	0.510	0.255	2.750	0.072	0.003
F x L x R	2	0.821	0.410	4.920	0.010*	0.004
F x I x R	1	0.012	0.012	0.200	0.654	0.000
T x L x I	4	1.624	0.406	5.580	0.0004*	0.008
T x L x R	4	0.568	0.142	1.950	0.106	0.003
T x I x R	2	0.295	0.148	1.800	0.174	0.001
L x I x R	2	0.374	0.187	2.890	0.063	0.002
F x T x L x I	4	0.870	0.217	2.670	0.035*	0.004
F x T x L x R	4	0.690	0.173	1.910	0.113	0.003
F x T x I x R	2	0.360	0.180	1.540	0.223	0.002
F x L x I x R	2	0.203	0.101	1.220	0.301	0.001
T x L x I x R	4	0.170	0.043	0.430	0.790	0.001
F x I x L x I x R	4	0.298	0.075	0.990	0.417	0.002
Subject (S)	31	31.388	1.013			

Table 3 (Continued)

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
F x S	31	6.742	0.217			
T x S	62	9.993	0.161			
L x S	62	13.267	0.214			
I x S	31	7.587	0.245			
R x S	31	3.598	0.116			
F x T x S	62	8.514	0.137			
F x L x S	62	5.204	0.084			
F x I x S	31	3.353	0.108			
F x R x S	31	2.714	0.088			
T x L x S	124	12.272	0.099			
T x I x S	62	8.120	0.131			
T x R x S	62	7.063	0.114			
L x I x S	62	5.781	0.093			
L x R x S	62	7.121	0.115			
I x R x S	31	2.184	0.070			
F x T x L x S	124	10.294	0.083			
F x T x I x S	62	4.419	0.071			
F x T x R x S	62	6.215	0.100			
F x L x I x S	62	5.738	0.093			
F x L x R x S	62	5.168	0.083			
F x I x R x S	31	1.766	0.057			
T x L x I x S	124	9.029	0.073			
T x L x R x S	124	9.011	0.073			
T x I x R x S	62	5.091	0.082			
L x I x R x S	62	4.009	0.065			
F x T x L x I x S	124	10.096	0.081			
F x I x L x R x S	124	11.194	0.090			
F x I x I x R x S	62	7.269	0.117			
F x L x I x R x S	62	5.130	0.083			
I x L x I x R x S	124	12.391	0.100			
F x T x L x I x R x S	124	9.368	0.076			

In addition to the main effects there were several interactions. Presentation format interacted with interference timing, $F(2, 62) = 4.860$, message length, $F(2, 62) = 31.050$, and interference type, $F(1, 31) = 18.630$. In addition, interference timing interacted with message length, $F(4, 124) = 8.600$, interference type, $F(2, 62) = 13.080$, and acknowledgement response, $F(2, 62) = 5.070$. Message length also interacted with

interference type, $F(2, 62) = 6.140$ and acknowledgement response, $F(2, 62) = 16.360$. There was also a 3-way interaction among presentation format, interference timing and interference type, $F(2, 62) = 4.070$. Another 3-way interaction was observed among format, message length, and acknowledgement response, $F(2, 62) = 4.920$. This interaction is shown in Figure 9 because it includes the effect of response.

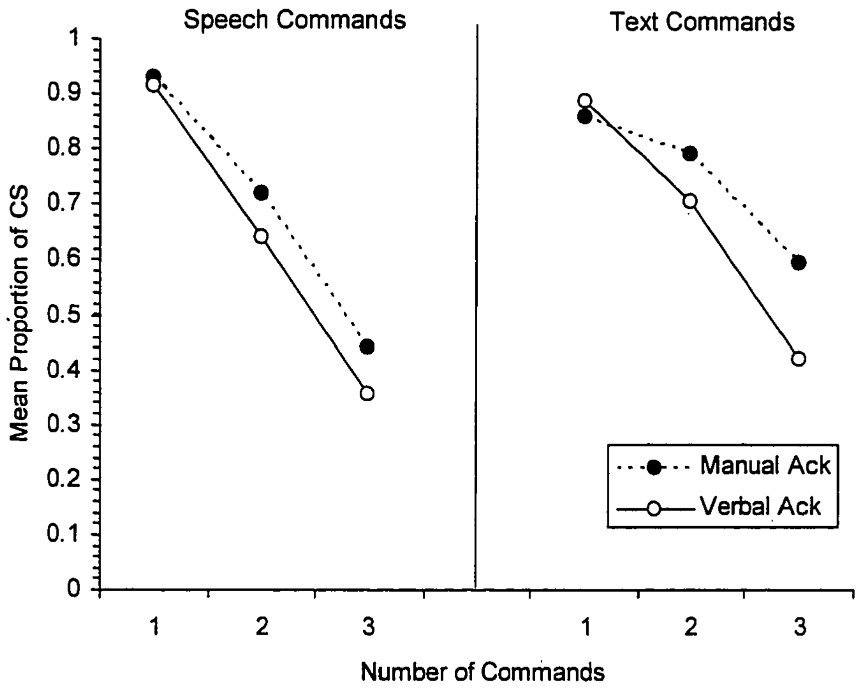

Figure 9. Mean proportion of CS for the interaction among format, message length, and acknowledgement response. Manual and verbal acknowledgement responses are plotted for each message length. The effects for speech are presented on the left and the effects for text are presented on the right.

A comparison of the means demonstrated that there were no differences between presentation formats with a verbal acknowledgement at the same message lengths. However, there was a difference between formats with a manual acknowledgement. Specifically, with respect to a manual acknowledgement, there was a lower proportion of CS in the text condition with one command as compared to speech. On the other hand,

there was a lower proportion of CS in the speech condition with two and three commands compared to text. In both speech and text conditions, there was a lower proportion of CS with a verbal acknowledgement at two and three commands compared to a manual acknowledgement. The magnitude of these differences was more pronounced when messages were presented as text.

There was also an interaction among interference timing, message length, and interference type, $F(4, 124) = 5.580$. Last, a significant 4-way interaction was obtained among format, interference timing, message length, and interference type, $F(4, 124) = 2.670$, and is shown in Figure 10.

In the speech condition, a comparison of the means demonstrated that in both before and after timing conditions there was a lower proportion of CS as message length increased at each command length within both verbal and CE interference. In the before timing condition, CE interference resulted in a lower proportion of CS compared to verbal interference with one command. There were no differences between verbal and CE interference at each message length in the after timing condition and the control condition. However, in the control condition, there was no difference between one and two commands during the verbal interference trials, but there was a lower proportion of CS with three commands. Also in the control condition, there was a lower proportion of CS as message length increased at each command length during the CE interference trials.

Between timing conditions, there were no differences for verbal interference with one and three commands. However, there was a lower proportion of CS in both before and after timing conditions with two commands compared to the control.

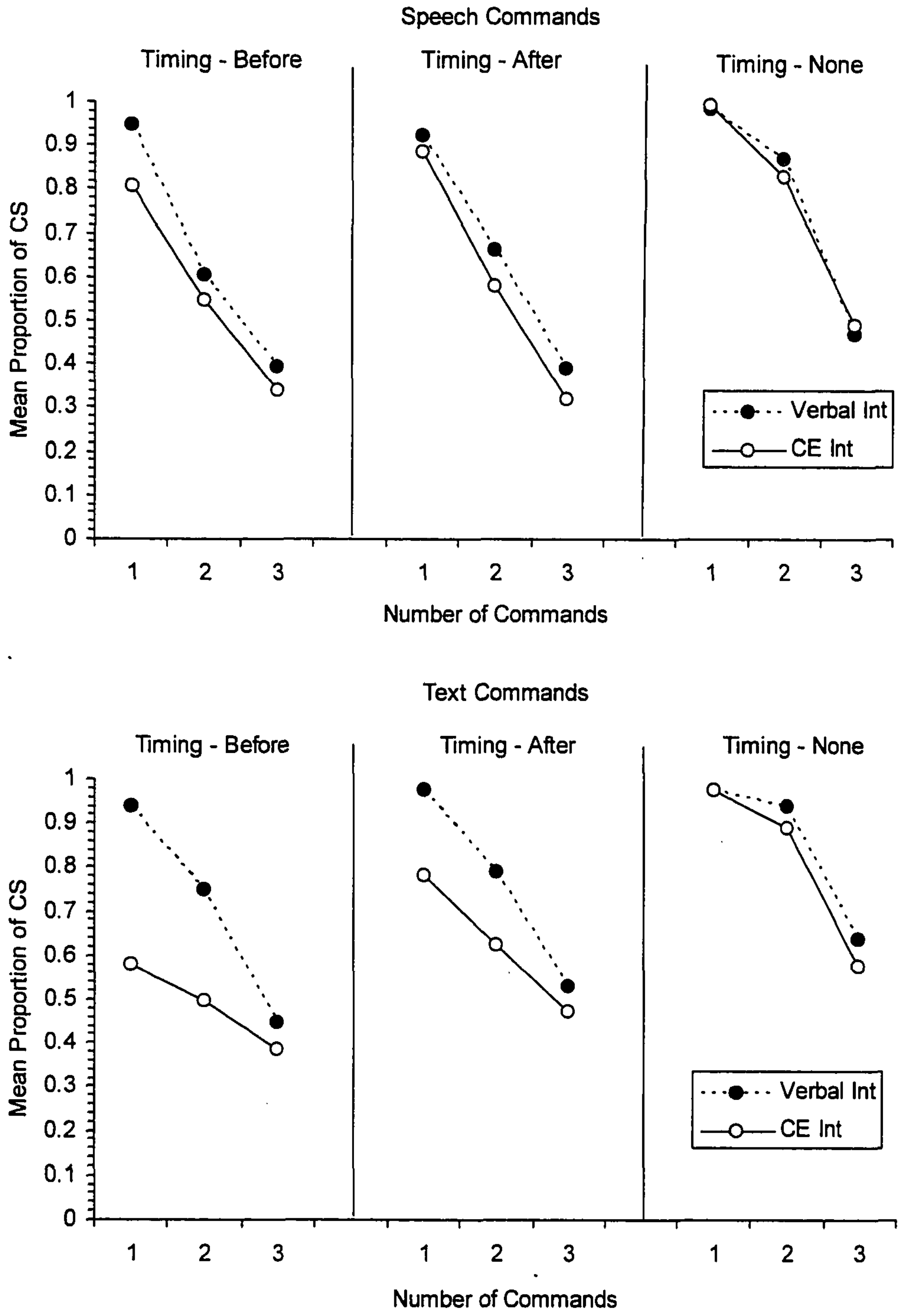

Figure 10. Mean proportion of CS for the interaction among format, interference timing, message length, and interference type. Verbal and CE interference are plotted for each message length and interference timing. Before, after, and no interference timing conditions are presented from left to right. The effects for speech are presented on top and the effects for text are presented on the bottom.

Between timing conditions with CE interference, there was no difference between before and after timings. However, with CE interference, there was a lower proportion of CS with one command in the before timing condition compared to the control, but there was no difference with one command between the after timing condition and the control. Within CE interference, before and after timing conditions did not differ with two and three commands. However, both before and after timing conditions with two and three commands resulted in a lower proportion of CS compared to the control at the same message lengths.

In the text condition, within the before timing condition with verbal interference there was a lower proportion of CS as message length increased at each command length. However, in the before timing condition with CE interference there were no differences between message lengths. In the before timing condition, there was a lower proportion of CS with CE interference compared to verbal interference with one and two commands, but not three commands. Within the after timing condition with both verbal and CE interference, there was a lower proportion of CS as message length increased at each command length. Also in the after timing condition, there was a lower proportion of CS with CE interference compared to verbal interference with one and two commands, but not three commands. In the control condition, there were no differences between one and two commands, but there was a lower proportion of CS with three commands as compared to one and two commands. Also in the control condition, there were no differences between verbal and CE interference at each message length.

Between timing conditions, there were no differences for verbal interference with one command. There was also no difference with verbal interference with two

commands between before and after timing conditions; however, both resulted in a lower proportion of CS than the control. At three commands with verbal interference, there was no difference between before and after timing conditions. However, there was a lower proportion of CS with a 3-command message in the before timing condition during verbal interference compared to the control, but there was no difference between the after timing condition and the control. Between timing conditions with CE interference, there was a lower proportion of CS with one command in the before timing condition compared to both the after timing condition and the control. In addition, with CE interference, there was a lower proportion of CS with one command in the after timing condition compared to the control. There was no difference with CE interference and two commands between before and after timing conditions. However, both before and after timing conditions with CE interference and two commands resulted in a lower proportion of CS as compared to the control condition. When there were three commands and CE interference, there were no differences between before and after interference timings. However, there was a lower proportion of CS with CE interference and three commands in the before timing condition compared to the control, but there was no difference between the after timing condition and the control.

Comparing speech and text, there were no differences with verbal interference in the before timing conditions with one and three commands. However, there was a lower proportion of CS with verbal interference in speech with two commands compared to text. In the before timing conditions with CE interference, there was a lower proportion of CS in the text condition with one command, but not with two and three commands. Comparing the after timing conditions between speech and text, there were no differences

in verbal interference with one and two commands, but there was a lower proportion of CS in the speech condition with three commands as compared to text. In the after timing conditions with CE interference, there were no differences between speech and text with one and two commands. However, there was a lower proportion of CS with CE interference and three commands in the speech condition as compared to text. In the control conditions, there were no differences during the verbal trials between speech and text with one and two commands, but there was a lower proportion of CS with three commands in the speech condition as compared to text. There were no differences between speech and text at each command length during the CE trials.

A comparison between the CSCO and CS measures showed that the main effects were the same with the exception of a significant effect of format as measured by CS. A comparison of the interactions between CSCO and CE demonstrated that 7 of 10 possible 2-way interactions were the same, whether significant or not. However, there was a significant format by response effect with CSCO that was not present with CS. Alternatively, there were significant timing by response and length by interference effects with CS that were not present with CSCO. There were 8 of 10 possible 3-way interactions that were the same. One difference was a significant interaction among timing, interference, and response with CSCO that was not present with CS. Also, there was a significant interaction among format, timing, and interference that was present with CS, but not with CSCO. There were also three of five possible 4-way interactions that were the same. A significant interaction among format, timing, interference, and response was present with CSCO, but not with CS. On the other hand, there was a significant interaction among format, timing, length, and interference with CS, but not

with CSCO. Finally, the 5-way interaction was not significant for both CSCO and CE measures.

Incorrect Controls

There was a total of 78 out of a possible 3,072 instances in which participants adjusted the wrong control. The frequencies for each variable are presented in Table 4. Because it was not possible to set incorrect controls when there were three commands, only command lengths of one and two are shown. Chi-square analyses were performed on each independent variable as shown in Table 5.

Table 4
Frequency Table for the Number of Incorrect Controls

Source	Frequency	Percent
Format		
Speech	32	41.03
Text	46	58.97
Timing		
Before	39	50
After	32	41.03
Never	7	8.97
Length		
1	27	34.62
2	51	65.38
Interference		
Verbal	25	32.05
CE	53	67.95
Response		
Manual	47	60.26
Verbal	31	39.74

There were significant differences between levels of timing where more incorrect controls were set when interference was present before and after acknowledgement as compared to the control condition. More incorrect controls were also set with two

commands as compared to one. Further, more incorrect controls were set when CE interference was present as compared to verbal interference.

Table 5

Chi-square Analyses for the Number of Incorrect Controls

Source	*df*	*N*	χ^2	*p*
Format	1	78	2.513	.113
Timing	2	78	21.769	<.0001*
Length	1	78	7.385	.007*
Interference	1	78	10.051	.002*
Response	1	78	3.282	.070

To determine if there were any trends among the variables, a 2 (format) x 2 (interference) x 2 (response) frequency table was calculated for the number of incorrect controls that were set. The results are shown in Table 6. Length was excluded from the frequency table because the chi-square analyses demonstrated that longer commands resulted in a greater number of incorrect controls set. Timing was also excluded because the only difference was between the control condition and the other two timing conditions. Thus, the control condition was excluded from the following 3-way frequency table so as not to confound the interference variable frequencies. Therefore, the seven incorrect controls set in the control condition were removed and the remaining 71 controls are presented.

The pattern of frequencies suggests that more incorrect controls are set when CE interference is presented with a text message as compared to a speech message. Additionally, there were more incorrect controls set with a manual acknowledgement response compared to a verbal response when CE interference was present in both speech and text.

Table 6

3-way Frequency Table for the Number of Incorrect Controls

Format	Interference	Response	Frequency	Percentage
Speech	Verbal	Manual	7	9.859
Speech	Verbal	Verbal	4	5.634
Speech	CE	Manual	12	16.901
Speech	CE	Verbal	7	9.859
Text	Verbal	Manual	5	7.042
Text	Verbal	Verbal	7	9.859
Text	CE	Manual	19	26.761
Text	CE	Verbal	10	14.085

Verbal Interference Task

Correct detections. The proportions of correctly detected targets during the call sign task were analyzed. A summary of the results for a 2 (format) x 2 (response) x 2 (timing) x 3 (length) ANOVA are shown in Table 7.

Table 7

Analysis of Variance for the Proportion of Verbal Interference Correct Detections

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
Format (F)	1	0.104	0.104	4.800	0.036*	0.006
Response (R)	1	0.463	0.463	10.130	0.003*	0.028
Timing (T)	1	0.057	0.057	2.160	0.152	0.003
Length (L)	2	0.794	0.397	18.630	<.0001*	0.046
F x T	1	0.005	0.005	0.380	0.541	0.000
F x L	2	0.028	0.014	0.620	0.542	0.002
F x R	1	0.010	0.010	0.690	0.414	0.001
T x L	2	0.036	0.018	0.950	0.392	0.002
T x R	1	0.035	0.035	1.360	0.252	0.002
L x R	2	0.011	0.006	0.260	0.769	0.001
F x T x L	2	0.000	0.000	0.000	0.997	0.000
F x T x R	1	0.023	0.023	1.260	0.271	0.001
F x L x R	2	0.060	0.030	1.400	0.253	0.004
T x L x R	2	0.003	0.001	0.060	0.941	0.000
F x T x L x R	2	0.039	0.020	0.810	0.450	0.002
Subject (S)	31	5.024	0.162			
F x S	31	0.672	0.022			
R x S	31	1.416	0.046			

Table 7 (Continued)

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
T x S	31	0.813	0.026			
L x S	62	1.321	0.021			
F x T x S	31	0.375	0.012			
F x L x S	62	1.402	0.023			
F x R x S	31	0.471	0.015			
T x L x S	62	1.162	0.019			
T x R x S	31	0.797	0.026			
L x R x S	62	1.343	0.022			
F x T x L x S	62	1.550	0.025			
F x T x R x S	31	0.578	0.019			
F x L x R x S	62	1.333	0.021			
T x L x R x S	62	1.399	0.023			
F x T x L x R x S	62	1.510	0.024			

There was a main effect of format, $F(1, 31) = 4.800$, where there was a lower proportion of correct target detections when commands were presented as speech (M = .913, SD = .162) as compared to text (M = .930, SD = .157). There was also a main effect for response, $F(1, 31) = 10.130$, where there was a lower proportion of correct target detections when a verbal acknowledgement was required (M = .904, SD = .177) compared to a manual acknowledgement (M = .939, SD = .138). Furthermore, there was a significant main effect of length, $F(2, 62) = 18.630$. The means and standard deviations for 1-, 2-, and 3-commands were .947 (SD = .132), .925 (SD = .153), and .892 (SD = .185), respectively. A comparison of the means demonstrated that each command length differed significantly from one another. Thus, there was a lower proportion of correct target detections with an increase in command length. There were no significant interactions for the proportion of correct detections.

Errors of Commission. The proportions of distractors responded to during the call sign task were also analyzed. A summary of the results for a 2 (format) x 2 (response) x

2 (timing) x 3 (length) ANOVA are shown in Table 8.

Table 8
Analysis of Variance for the Proportion of Verbal Interference Errors of Commission

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
Format (F)	1	0.005	0.005	0.450	0.510	0.001
Timing (T)	1	0.001	0.001	0.150	0.705	0.000
Length (L)	2	0.174	0.087	7.840	0.001*	0.024
Response (R)	1	0.098	0.098	5.190	0.030*	0.013
F x I	1	0.003	0.003	0.280	0.601	0.000
F x L	2	0.025	0.013	1.690	0.193	0.004
F x R	1	0.007	0.007	0.730	0.401	0.001
I x L	2	0.003	0.002	0.210	0.814	0.000
I x R	1	0.003	0.003	0.280	0.601	0.000
L x R	2	0.013	0.007	0.870	0.425	0.002
F x I x L	2	0.038	0.019	1.530	0.225	0.005
F x I x R	1	0.009	0.009	0.910	0.348	0.001
F x L x R	2	0.035	0.017	2.200	0.119	0.005
I x L x R	2	0.036	0.018	1.930	0.154	0.005
F x I x L x R	2	0.025	0.013	1.230	0.299	0.004
Subject (S)	31	1.127	0.036			
F x S	31	0.343	0.011			
I x S	31	0.216	0.007			
L x S	62	0.688	0.011			
R x S	31	0.583	0.019			
F x I x S	31	0.365	0.012			
F x L x S	62	0.467	0.008			
F x R x S	31	0.294	0.009			
I x L x S	62	0.525	0.008			
I x R x S	31	0.365	0.012			
L x R x S	62	0.474	0.008			
F x I x L x S	62	0.777	0.013			
F x I x R x S	31	0.312	0.010			
F x L x R x S	62	0.489	0.008			
I x L x R x S	62	0.576	0.009			
F x I x L x R x S	62	0.634	0.010			

There was a significant main effect of length during the call sign task, $F(2, 62) = 7.840$. The means and standard deviations for 1-, 2-, and 3-commands were .032 (SD = .089), .042 (SD = .102), and .058 (SD = .111), respectively. A comparison of the means

demonstrated that a higher proportion of errors was made with a 3-command message as compared to a 1-command message. There was also a significant main effect of response, $F(1, 31) = 5.190$, where a higher proportion of errors was made when a verbal acknowledgement was required ($M = .052$, $SD = .111$) as compared to a manual acknowledgement ($M = .036$, $SD = .091$). There were no significant interactions for the proportion of errors of commission.

CE Interference Task

Correct responses. The proportions of correct responses to the fuel calculation questions during the CE interference task were analyzed. A summary of the results for a 2 (format) x 2 (response) x 2 (timing) x 3 (length) ANOVA is shown in Table 9. There was a significant effect of response, $F(1, 31) = 8.220$. The means demonstrated that there was a lower proportion of correct responses with a verbal acknowledgement (M = .259, SD = .235) compared to a manual acknowledgement (M = .285, SD = .248). There were no significant interactions for the proportion of correct responses.

Table 9
Analysis of Variance for the Proportion of CE Task Correct Responses

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
Format (F)	1	0.061	0.061	0.470	0.496	0.002
Timing (T)	1	0.012	0.012	0.340	0.562	0.000
Length (L)	2	0.006	0.003	0.060	0.939	0.000
Response (R)	1	0.269	0.269	8.220	0.007*	0.008
F x T	1	0.038	0.038	1.280	0.266	0.001
F x L	2	0.058	0.029	0.780	0.461	0.002
F x R	1	0.002	0.002	0.030	0.855	0.000
T x L	2	0.061	0.031	0.830	0.440	0.002
T x R	1	0.133	0.133	2.600	0.117	0.004
L x R	2	0.009	0.004	0.110	0.893	0.000
F x T x L	2	0.133	0.066	1.690	0.193	0.004
F x T x R	1	0.122	0.122	1.770	0.194	0.004
F x L x R	2	0.022	0.011	0.340	0.712	0.001

Table 9 (Continued)

Source	*df*	*Type III SS*	*MS*	*F*	*p*	ηp^2
T x L x R	2	0.058	0.029	1.020	0.367	0.002
F x T x L x R	2	0.103	0.051	1.900	0.159	0.003
Subject (S)	31	26.595	0.858			
F x S	31	3.974	0.128			
T x S	31	1.106	0.036			
L x S	62	3.068	0.049			
R x S	31	1.016	0.033			
F x T x S	31	0.922	0.030			
F x L x S	62	2.276	0.037			
F x R x S	31	1.700	0.055			
T x L x S	62	2.272	0.037			
T x R x S	31	1.594	0.051			
L x R x S	62	2.436	0.039			
F x T x L x S	62	2.441	0.039			
F x T x R x S	31	2.137	0.069			
F x L x R x S	62	1.978	0.032			
T x L x R x S	62	1.775	0.029			
F x T x L x R x S	62	1.675	0.027			

Attempted Questions. The proportion of fuel calculation questions attempted during the CE interference task was assessed to ensure that participants were in fact performing the task. A 2 (format) x 2 (response) x 2 (timing) x 3 (length) ANOVA was performed on the proportion of attempted questions.

There was significant main effect of interference timing, $F(1, 31) = 7.270$, where a lower proportion of questions were attempted during the CE task when the task was performed before acknowledgement ($M = .653$, $SD = .213$) compared to after acknowledgement ($M = .673$, $SD = .216$). There was also a significant main effect of acknowledgement response, $F(1, 31) = 9.020$, where a lower proportion of questions was attempted with a verbal acknowledgement ($M = .649$, $SD = .218$) as compared to a manual acknowledgement ($M = .677$, $SD = .211$). In addition, there was also a

significant 4-way interaction among format, interference timing, message length, and acknowledgement response, $F(2, 62) = 3.960$.

However, there is limited confidence in this measure given differences in how participants responded. Recall that a question was counted as an attempt even if a single character was typed in the entry field on the form. However, several participants studied the problem for several seconds before entering any values into the field. Other participants typed as they worked through a problem. Thus, this measure may not be an accurate reflection of CE processing as much as it is a measure of strategy or a methodological limitation of response duration. Furthermore, the results surrounding the effects of CE interference for the control setting measures demonstrated that participants were engaged in the task. Therefore, no further discussion of this measure will follow.

Verbal Readback Performance

To verify that readbacks were being performed correctly, a frequency count was performed on the number of correctly and incorrectly set controls when there were correct, incorrect, and missed readbacks. There was a total of 4,608 commands read back. This reflects half of the commands in the experiment as the other half required a manual acknowledgement. A summary for these data is shown in Table 10.

Table 10
Frequency Count of Control Setting Performance as a Function of Readback Performance

Control Setting	Readback			
	Correct	Incorrect	Missed	Total
Correct	2,488	46	79	2,613
Incorrect	454	643	898	1,995
Total	2,942	689	977	4,608

These data suggest that the probability of correctly setting a control with the correct readback was .952. The probability of setting a control correctly with the incorrect readback was .018 and with no readback was .030. On the other hand, the probability of setting a control incorrectly with the correct readback was .228. The probability of setting a control incorrectly with the incorrect readback was .322 and with no readback was .450.

Response Time

Response times were obtained for the entire length of each trial. Thus, this measure was confounded by length, acknowledgement response, and interference timing. For instance, as the number of commands increased so did RT. Further, with respect to acknowledgement response, a manual response (i.e., button press) was always shorter than a verbal readback. Also, the trial was always 15 s shorter in duration when there was no interference present. Therefore, the length and response variables and the "none" level within timing were removed prior to analysis. A 2 (format) x 2 (interference) x 2 (timing) ANOVA was performed on the RT to each trial. There was a significant Format x Interference x Timing interaction, $F(1, 31) = 4.30$, $p = .046$, $MSE = 63.175$, $\eta p^2 = <.001$. The analysis revealed that that when text messages were presented with CE interference after acknowledgement, setting all of the controls (correctly or incorrectly) took 1.8 s to 3.3 s longer within a 45 s trial. There is limited confidence in these results for several reasons. First, the more difficult the trial, the shorter the RT may actually be because participants did not set what they could not remember – thus, there may be an inverse relationship between difficulty and RT. In this case, fewer controls in memory would result in fewer controls to set which would take less time. Second, the data were

not consistent with the primary dependent measures (e.g., CSCO and CS) where CE interference presented *before* acknowledgement had the greatest negative effect. Third, the effect only accounted for .06% of the variance. Fourth, the range of the standard deviations was very large, 11 s to 15 s. Therefore, no further effects will be reported for this measure.

Strategy Questionnaire

A short questionnaire was administered at the end of the second session to determine if participants were using a verbal strategy for the CE interference task and to determine if they were able to rehearse information during both interference tasks. The first set of questions asked participants about their strategy for performing the CE interference task. All but one participant calculated the fuel task using numeric operations while one participant identified verbal components with the numbers (i.e., similar to a word problem). The second set of questions asked participants if they used rehearsal during the call sign task and fuel calculation task. All 32 participants reported that they used rehearsal to remember the commands during the call sign task and 25 participants reported that used rehearsal to remember the commands during the fuel calculation task.

DISCUSSION

In aviation, the communication process is defined by message transmission, reception, comprehension, acknowledgement, and execution. The current radio communications system suffers from a host of problems that stem from both limitations of the radio technology and limitations of human performance. One method to address these problems is with a text-based communication technology called datalink in which text messages are sent between ATC and the flight deck. The messages are read rather than listened to and acknowledged with a button push on the CDU rather than a verbal readback. Although datalink was designed to alleviate some problems with radio communications, it now appears that there may be human performance concerns related to the differences between processing speech and text information as well as the method for responding to messages. Specifically, pilots must monitor and process other sources of information within the cockpit, sometimes while communicating with ATC. Thus, there may be differences between speech and text and their susceptibility to interference from other sources of information from within the cockpit. Furthermore, the timing of the interference in the communication process may also have an impact on message execution.

The aim of the present study was to address the response portion of the communication process (i.e., acknowledgement and execution) and the timing of interference on command execution performance. Participants were presented with speech and text messages that varied in length from one to three commands and were required to execute the commands on a control panel in a flight simulator. This study differed from previous studies of Risser and his colleagues (Risser et al., 2002, 2003,

2004; Scerbo et al., 2003) in two distinct ways. First, the nature of the response, either a manual or verbal acknowledgement, was examined. Second, the timing of interference was presented before or after the acknowledgment response. As described earlier, Risser et al. (2002, 2003) and Scerbo et al. (2003) presented interference during the presentation of commands thereby disrupting the encoding process. However, Risser et al. (2004) presented the interference tasks after the presentation of commands. Regardless of timing condition, interference in the present study was also presented subsequent to the commands.

Acknowledgement Response

As noted earlier, acknowledgement responses differ between datalink and voice environments. Datalink messages require a button push while responses to speech messages require a readback. According to multiple-resource theory (Wickens, 1984) more interference was expected between the cognitive processing stage and the response stage when the same codes were used. Thus, a verbal acknowledgement response would share similar resources with the commands in memory that use a verbal processing code. Therefore, poorer performance was expected with a verbal acknowledgement as compared to a manual acknowledgement which utilized separate resources. Consistent with this hypothesis, a verbal acknowledgement resulted in a lower proportion of CSCO and CS than a manual acknowledgement.

This effect of acknowledgement response was further supported by performance on both the call sign and fuel calculation tasks. In the call sign task, there was a lower proportion of correct detections and a greater proportion of errors of commission when a verbal acknowledgement was required. There were also fewer correct responses for the

fuel calculation task when a verbal acknowledgement was required. These measures demonstrated that the additional resources required by a verbal acknowledgement negatively affected performance on both interference tasks. It appears that the verbal acknowledgement consumed more processing resources in general as compared to the manual acknowledgement. In other words, more effort was required to produce a verbal readback than to push a button. As expected, the verbal acknowledgement competed for similar verbal resources across stages of processing and resulted in decreased performance.

An argument can be made that the purpose of readback is not only for confirmation but also rehearsal. However, consistent with the theoretical predictions that verbal response resources would compete with verbal processing code resouces, readback has been shown to create verbal output interference and disrupt performance (Schneider et al., 2000). This effect was also observed in the verbal readback data from the present study. Although only 64% of all readbacks were correct, the probability of correctly setting a control with a correct readback was .952. Thus, when participants repeated commands correctly, they almost always set the controls correctly. However, the remaining 36% of readbacks were either incorrect or missed and the probability of correctly setting controls was .018 and .030, respectively. Therefore, these data suggest a failure during the processing of information rather than in its execution.

Response, Format, and Length. Although the working memory model of Baddeley and Hitch (1974) does not make specific predictions regarding the response stage of processing, it could be inferred that the additional use of verbal resources with a verbal acknowledgement would interfere with commands in the phonological loop.

Further, as previously mentioned, text does not have direct access to the phonological loop because it must be recoded from the visual modality into a verbal code which requires additional processing resources. This additional processing can make text more susceptible to interference (Risser et al., 2002; Scerbo et al., 2003). In addition, verbal readback can create verbal output interference which has been shown to disrupt longer and more redundant text-based navigation instructions (Schneider et al., 2000). However, according to multiple-resource theory (Wickens, 1984, 1991b), it was argued that no differences between presentation formats should be expected because both speech and text utilize a verbal processing code once messages are encoded. Therefore, in the present study it was expected that messages would benefit from a manual acknowledgement as compared to a verbal acknowledgement regardless of format because a manual response does not require the use of the phonological loop and does not share similar resources with commands in memory.

There was partial support for this hypothesis. No differences in the proportion of CSCO between formats were observed with a verbal acknowledgement. However, performance was better with a manual acknowledgment in the text as compared to speech condition. This effect was further qualified by message length as shown in Figure 6.

It was expected that longer messages would decrease performance by increasing the demands on working memory resources and disrupting rehearsal. According to multiple-resource theory (Wickens, 1984, 1991b), longer messages would increase memory demands by consuming more verbal resources leaving fewer resources for additional processing. The working memory model (Baddeley & Hitch, 1974) suggests that increasing the number of commands would require more verbal resources and disrupt

the rehearsal of information in the phonological loop as demonstrated by the word length effect (Baddeley et al., 1975). This effect was demonstrated by a lower proportion of CSCO and CS with an increase in message length. In addition, the proportion of verbal task correct detections was lower with longer messages. Also, there were more incorrect controls set and a lower proportion of verbal task errors of commission as the number of commands increased. Overall, increases in message length confirmed that performance suffered as the verbal load on working memory increased.

As previously discussed and consistent with predictions, a verbal acknowledgement had the same negative effect on both speech and text because both share a verbal processing code. In addition, performance decrements were greater with longer messages because more verbal resources were utilized which disrupted rehearsal. Therefore, a verbal acknowledgement also had the same increasingly negative effect on both presentation formats with an increase in message length as shown in Figure 6. Contrary to expectations, text but not speech messages benefited from a manual acknowledgement, although this advantage was limited to the longest messages (i.e., three commands). This effect suggests that memory load moderated the efficacy of each format. A manual acknowledgement was particularly beneficial for longer messages because it did not compete for the verbal resources needed for additional commands. The benefit for the manual response in the text as compared to the speech condition is possibly due to additional rehearsal time. In the present study, text commands could have been processed more efficiently than speech commands given the same presentation times. As described earlier, all 3-command text messages were presented for 7.5 s. Recall that text messages were displayed for the median duration of a speech message at

the same length. Thus, it is likely that three text commands could be read and rehearsed within the same time needed to listen to the three speech commands.

The same effect of format, length, and response was also observed with the CS measure as shown in Figure 9. However, there were two primary differences between the CS and CSCO measures. First, regarding the speech condition, there was a benefit for manual acknowledgement as compared to verbal acknowledgements with two and three commands. In contrast, there was no difference between response types across message length in the speech condition with the CSCO measure. Second, there was an advantage for a manual acknowledgement in the text as compared to the speech condition with two commands. With the CSCO measure, presentation formats did not differ at two commands with a manual acknowledgement. Overall, these findings imply that there is an advantage for a manual acknowledgement at longer message lengths because it does not use verbal resources required by a verbal acknowledgement. However, when there is no restriction regarding order of execution (i.e., as measured by CS), the performance advantage observed with a manual acknowledgement is also present in the speech condition. These results suggest that maintaining the serial order of verbal information imposes further demands on working memory and that it is advantageous to use separate resources to acknowledge a message as message length increases and working memory begins to reach capacity.

Another interesting difference, albeit small, was observed between formats with both CSCO and CS: there was actually a slight disadvantage with a manual acknowledgement when a 1-command message was presented as text rather than speech. Recall that a simple button push was required to acknowledge a message manually.

Thus, participants were able to respond faster with a manual acknowledgement than with a verbal readback. In addition, participants may have responded faster to shorter messages. Given that speech has direct access to the phonological store, it is likely that performance was better with short speech messages. Therefore, it appears the speed of a manual response with a short text message invited more error because participants may have responded too quickly and did not encode the shorter text messages properly.

Overall, the combination of format, message length, and acknowledgement response demonstrated that with longer message lengths, a verbal acknowledgement can itself be a form of interference when compared to a manual acknowledgement. This is consistent with multiple-resource theory (Wickens, 1984, 1991b) in that using the same code between processing and response stages can introduce interference. This is also with consistent with the verbal output interference found by Schneider et al. (2000); however, they reported that verbal readback had a greater negative effect on performance with longer text as compared to speech messages. In the present study, as predicted, no performance differences with a verbal acknowledgment were found between presentation formats. There are several differences between the two studies that might account for this discrepancy. First, Schneider et al. used navigation commands (i.e., turn left one square) with a spatial navigation task as their measure of performance. Therefore, participants may have been able to encode the commands using spatial rather than verbal resources. By contrast, in the present study participants had to execute commands by setting controls which required more verbal and less spatial resources. Therefore, consistent with multiple-resource theory, once the commands are encoded verbally, there should be no format differences with a verbal acknowledgement. Second, Schneider et

al. presented text messages on the side of the screen with one word on each line and next to the navigation grid. This suggests two methodological concerns. First, presenting words individually does not facilitate the chunking of information and can decrease recall (Miller, 1956). Second, because the words were presented next to the navigation grid, it is likely that this created visual resource competition between the text and the grid which hindered the ability to encode the text messages properly. By contrast, speech commands could be heard while simultaneously scanning the navigation grid. Thus, an advantage for speech commands would be expected because separate resources are being used. A similar finding was observed by Risser et al. (2004) who displayed text commands and a visual interference task on a separate screen located next to the control panel display. Negative effects of visual task interference were found in the text but not speech condition. The authors concluded that the visual complexity from two separate sources of visual information added to visual scanning efforts that were not present in the speech condition. In other words, information presented auditorily permits simultaneous visual scanning of a display. On the other hand, information presented visually will prohibit visual scanning from a secondary visual source of information and is related to structural interference associated with input modalities rather than central processing interference associated with cognitive performance (Wickens, 1991b).

Of note, the acknowledgement stage in the communication process is not expected to be a form of interference. The intent of acknowledgement is to not only communicate a shared understanding between two parties, but also to reinforce the message already encoded. By its nature, it can be argued that an acknowledgement may be a form of interference if it shares similar resources with information in memory. A

verbal acknowledgement would be one example. However, an acknowledgement response is distinct from an interference task in that it does not require the user to switch tasks – it is a confirmation of information already in memory. Although they both require verbal resources, the verbal interference task requires verbal information that differs from commands in memory and a verbal acknowledgement uses the same source of verbal information as the commands in memory. Further, according to multiple-resource theory (Wickens, 1984), even when similar processing codes are used there should be less interference between stages of processing. Thus, the magnitude of the acknowledgement response effect was expected to be less than that of the interference task effect.

Interference Type. There was also an expectation that control setting performance would be affected by the interaction between acknowledgement response and type of interference. Regarding interference type, both CE and verbal interference tasks were expected to have a negative effect on commands in memory, but the effect of CE was expected to be greater. Based on multiple-resource theory (Wickens, 1984), the verbal task was expected to interfere with commands in memory because they share a similar processing code. Similarly, according to the working memory model (Baddeley & Hitch, 1974), verbal interference was expected to disrupt memory due to verbal resource competition in the phonological loop which is consistent with the unattended speech effect (Salame & Baddeley, 1982). Regarding the CE task, it was expected that CE interference would disrupt rehearsal more than verbal interference because CE processes consume more resources regardless of processing code as hypothesized by the working memory model (Baddeley & Hitch, 1974) and demonstrated by previous research (Risser

et al., 2002; Risser et al., 2003, 2004; Scerbo et al., 2003). In the present study, this hypothesis was confirmed by a lower proportion of CSCO and CS with the presence of CE as compared to verbal interference. This effect was also supported by more incorrect controls set when CE interference was present. Furthermore, the postexperimental questionnaire indicated that participants calculated the fuel task using numeric operations rather than a verbal code, thus confirming that executive processes were used. In addition, only 75% of participants indicated they were able to use rehearsal as a strategy during the CE task. By contrast, all participants reported they were able to use rehearsal during the verbal task. This suggests that the CE interference task was more difficult and participants were less likely to rehearse. Therefore, more resources were used to process the CE task than the verbal task which confirms the negative effects of CE interference on performance.

Response and Interference Type. The effects of acknowledgement response were also expected to interact with the type of interference. Specifically, it was hypothesized that a verbal acknowledgement would result in poorer performance in the context of CE as compared to verbal interference because a verbal acknowledgement uses more resources than a manual acknowledgement and CE processing uses more resources than verbal processing. Although the results for either measure, CSCO or CS, were not statistically significant, there was a trend indicating reduced performance when a verbal acknowledgment was combined with CE interference.

Although the expected interaction between acknowledgement response and interference type was not observed in the primary dependent measures, there is some evidence for the effect in the error measures. Specifically, the observed pattern of

frequencies for incorrect controls demonstrated that there were more incorrect controls set when CE interference was presented with a text as compared to a speech message as shown in Table 6. This finding is consistent with Risser et al. (2004) and Scerbo et al. (2003) who observed more control setting errors in text conditions with CE interference. In these studies, the authors concluded that text was more susceptible to interference because it does not have direct access to the phonological store and because more resources were required for the phonological recoding of text.

To reiterate, poorer performance was expected in the present study with a verbal acknowledgement and CE interference. One explanation surrounding the lack of significance for this predicted effect may be tied to message length. As previously discussed, a verbal acknowledgement differed from a manual acknowledgement only with longer text messages. However, the expected interaction between response and interference type for control setting performance was similarly qualified by format and interference timing for CSCO as shown in Figure 8.

Interference Timing

With regard to interference timing, it was expected that interference prior to acknowledgement would increase task switching and impair performance more than interference after acknowledgement. For example, after the commands were presented, the interference task was to be processed before returning to the acknowledgment stage in the communication process. Although multiple-resource theory does not address resources associated with task switching, Wickens (1991b) offers that interference can occur between two tasks using cognitive programs that share similar processing codes. Baddeley et al. (2001) have shown that both executive and verbal processes are

associated with the control of task switching. Thus, task switching should disrupt the communication process by consuming more resources and hinder the rehearsal process. Specifically, it was expected that interference presented before an acknowledgement would result in more task switching than when presented after an acknowledgement. This hypothesis was supported by a lower proportion of CSCO and CS when interference was presented before acknowledgement. In addition, there was a lower proportion of CSCO and CS in both the before and after timing conditions as compared to the control condition. Further support for this hypothesis was demonstrated by more incorrect controls set when interference was presented before an acknowledgement. Collectively, these findings confirm the idea that interference presented before rather than after acknowledgement has a greater negative effect on performance because alternating tasks utilize more verbal and executive resources.

Format, Interference Timing, Interference Type, and Response. An analysis of the CSCO measure also produced a 4-way interaction among format, interference timing, interference type, and response as shown in Figure 8. A detailed analysis of this interaction revealed that the hypothesis regarding a verbal acknowledgement response and CE interference was supported, but only in the text condition. Furthermore, this effect only occurred when interference was presented before acknowledgment. Thus, performance was poorest when messages were presented as text and CE interference was presented prior to a verbal acknowledgment as compared to verbal interference. Under these specific conditions memory demands are highest; thus, CE interference had the greatest negative effect because it used more resources than verbal interference.

It appears that larger differences between CE and verbal interference presented

both prior to and following acknowledgement were observed with text as compared to speech commands. This is consistent with previous studies that demonstrated more errors were made with CE interference when messages were presented as text as compared to speech (Risser et al., 2004; Scerbo et al., 2003). Scerbo et al. presented interference simultaneously with the commands. In contrast, Risser et al. presented interference after the commands. However, in both studies it was concluded that the phonological recoding of visual-verbal information required more resources; therefore, text information was negatively affected to a greater degree by the presentation of CE interference. In the present study, the same principles applied. The presentation of CE interference before acknowledgment not only resulted in an immediate task switch, but also a switch to the more difficult of the two interference tasks thus utilizing more resources and decreasing the opportunity for proper encoding and rehearsal. Moreover, because text was affected most by immediate CE processing as shown by both Risser et al. and the present study, it suggests that the recoding of text is not an immediate process.

Interference Timing, Response, and Interference Type. It was expected that the negative effects of interference presented prior to a verbal acknowledgement would be greater than when presented after a verbal acknowledgement. As previously discussed, a manual acknowledgement required fewer and separate resources from the commands in memory which improved performance over a verbal acknowledgement. On the other hand, a verbal acknowledgement was expected to share similar resources with commands in memory requiring more resources. As expected, interference presented before acknowledgement resulted in poorer performance because more task switching was required.

The findings, however, were not consistent with the predicted interaction between interference timing and acknowledgement response. Although this effect was not statistically significant, it was qualified further by presentation format and interference type. As previously discussed, performance decrements were greater with a verbal acknowledgement in the context of CE as opposed to verbal interference when the interference task was presented before an acknowledgement. However, this was also true for a manual acknowledgement. Therefore, there were no differences between types of acknowledgements when interference occurred before acknowledgment – there were only difference between types of interference.

However, there were differences between acknowledgement responses when interference was presented *after* acknowledgement. This finding was opposite of expectations but consistent with other results in the aforementioned interaction among format, timing, interference type, and response. Performance was better when verbal interference was presented after a manual acknowledgement in the text as compared to speech condition. This suggests that control setting performance was higher with a manual acknowledgement because it did not compete with the verbal resources. Furthermore, this effect was evident in the text condition because, as previously discussed, a manual acknowledgment improved performance with longer text messages due to less resource competition when memory was reaching capacity. Although the observed effect benefited from a manual response, it also showed no differences between speech and text with a verbal acknowledgement. This supports the conclusions discussed earlier regarding the interaction among format, response, and length: no differences were found between formats with a verbal acknowledgement at each message length because

both speech and text use a verbal processing code.

The previously discussed advantage for verbal over CE interference when presented before acknowledgment was inconsistent with predictions surrounding interference type. It was hypothesized that there would be no difference between interference types presented before a verbal acknowledgement. This prediction was based on evidence from a working memory model perspective suggesting that both CE resources and the phonological loop are utilized in the control of task switching (Baddeley et al., 2001; Baddeley, 2002). The results provided partial support for this hypothesis. There was no difference between interference types before a verbal acknowledgment in the speech condition, but there was a decrease in performance with CE as compared to verbal interference in the text condition. Although this effect was statistically significant, it was further moderated by format as seen in Figure 8. This suggests that although the CE task was difficult, it had the same effect as verbal interference when speech messages were presented. Therefore, this supports the earlier conclusion that text more than speech was negatively affected by CE processing immediately after the presentation of the commands and before an acknowledgement.

Interference Timing, Length, and Interference Type. As previously stated, longer messages were expected to produce a greater decrement in performance because they use more verbal resources in the phonological loop, which in turn, disrupts rehearsal. Therefore, CE and verbal sources of interference were expected to produce a decrease in performance with longer messages. Furthermore, because CE processes utilize more resources than verbal processes, the negative effect of CE interference was expected to be greater. The magnitude of the differences between types of interference, however, was

expected to decrease with more commands because resources would begin to reach capacity as demonstrated by Scerbo et al. (2003). This effect was observed with the CS measure and although the same pattern was evident in the CSCO measure, it was not statistically significant. The difference between the two measures is likely the result of the more stringent requirements for CSCO. As previously discussed, the need to execute commands in order may use more resources, thus potentially minimizing the differences between interference types. However, for the CSCO measure, this length by interference type prediction was qualified further by the effects of interference timing as shown in Figure 7.

Consistent with the hypothesis of message length and interference type, there were fewer CSCO when interference was present with longer messages. In addition, the magnitude of the differences between verbal and CE interference decreased with longer messages. Furthermore, there was a lower proportion of CSCO with CE as compared to verbal interference which suggests that CE processes required more resources than verbal processes. For the CSCO measure, these effects were further moderated by interference timing. The magnitude of the differences between interference types for fewer commands was greater when interference was presented before as compared to after acknowledgement. Consistent with the previous discussion on timing, this implies that the increased resource demand resulting from task switching was negatively affected more by CE interference than by verbal interference. In fact, the proportion of CSCO under CE interference was lower than in the control condition at each command length which suggests that it disrupted rehearsal at all levels of memory load. In contrast, verbal interference only differed from the control condition when there were two commands.

Therefore, verbal interference did not have an impact on rehearsal until there was a moderate load on working memory (i.e., two commands). It appears that when memory load is minimal (i.e., one command), unlike CE interference, rehearsal is still possible with verbal interference. On the other hand, when memory load is at or near capacity (i.e., three commands), the negative effects of verbal interference only show up before acknowledgement, because additional resources are required for task switching. Therefore, as resources in the phonological loop reach capacity with an increase in the number of commands, the type of interference is less important.

Collectively, these results suggest that there are differential effects of timing on types of interference as a function of resource capacity limitations. Specifically, executive processing will impair memory performance regardless of its timing and memory load; however, the negative effects will be greatest amid an increase in task switching. Moreover, verbal processing will only impair memory at moderate memory loads and when it also is associated with an increase in task switching.

Format, Interference Timing, Length, and Interference Type (CS). The previously discussed interaction among interference timing, message length, and interference type as measured by CSCO was also observed with the CS measure; however, the interaction was further qualified by presentation format as shown in Figure 10. For the CS measure, the magnitude of the differences between interference types was larger in the text as compared to the speech condition. Further, CE interference had a consistently greater negative effect than verbal interference. Moreover, the magnitude of these differences between interference types was greatest when interference was presented before acknowledgement in text as compared to speech. More specifically, the only difference

between interference types was isolated to lower performance for CE as compared to verbal interference when the interference task preceded acknowledgement in the speech condition. In contrast, CE as compared to verbal interference resulted in lower performance with both one and two commands prior to acknowledgment in the text condition. Similarly, there was no difference between interference types when the interference task followed acknowledgement in the speech condition. Again, performance was poorer with CE as compared to verbal interference with one and two commands when it followed an acknowledgement in the text condition. Although interference type and message length had the same effects under both timing conditions for text, the magnitude of the differences was greater when interference was presented before as compared to after acknowledgement. In fact, CE processing had the same negative effects on text when it preceded acknowledgement regardless of message length. Therefore, it can be concluded that CE processing prior to acknowledgement disrupted both rehearsal and encoding for text commands. On the other hand, CE interference following acknowledgement only disrupted the rehearsal process.

Consistent with predictions for message length and interference, there was no difference between interference types with longer messages because resources were already at capacity. Also consistent with previously discussed CSCO effects, there was a greater negative effect of CE processing on text messages, and more so when presented before an acknowledgement. Again, this effect is likely due to the extra resources required for the phonological recoding of visual-verbal information at the same time extra resources are required for an immediate switch to a task requiring CE processing. This suggests that CE processing can disrupt both rehearsal and encoding for text more than

speech messages even at minimal to moderate working memory loads. On the other hand, the effects of verbal interference were essentially the same between speech and text. In addition, verbal interference only differed from the control condition at moderate memory loads with speech commands. In contrast, verbal interference differed from the control condition with both moderate and high memory loads with text messages. Although verbal interference had greater negative effects on text than speech, it was affected less by timing and length than CE interference. This can be attributed to fewer resources used during verbal interference task processing where more participants used rehearsal as a strategy.

Summary

At this point it may be helpful to summarize the general findings surrounding acknowledgement response and interference timing. Regarding acknowledgement response, there was an advantage for a manual acknowledgement for longer text messages and when verbal interference was presented after acknowledgement with text commands. These effects were expected because a manual acknowledgement uses fewer and separate resources than a verbal acknowledgement. Thus, there were no distinct advantages for a verbal acknowledgement. Regarding interference timing, memory is more susceptible to the processing of additional tasks immediately after the to-be-remembered information because of the additional resource demands imposed by task switching and this effect is greater with CE interference as compared to verbal interference. Furthermore, differences between interference types are exacerbated prior to an acknowledgement.

Regarding the CSCO and CS measures, the main effects were the same for each

measure with the exception of presentation format. There was an advantage for text messages when measured by CS because, as previously discussed, text may have allowed for more rehearsal. In addition, there was no restriction on the order of execution with CS and eliminating the order requirement may have freed additional resources. However, it should be noted that the format effect accounted for the least amount of variance among all main effects. Further, most of the 2- and 3-way interactions were the same with each measure. However, there was a difference with the highest order 4-way interactions. Specifically, CSCO accounted for acknowledgement response while CS accounted for length among format, interference timing, and interference type. Arguably, it makes sense that when order is not a requirement, CS accounts for message length in the highest order interaction because longer messages (which would have more requirements for execution order with CSCO) are unaffected by the less stringent criterion.

In the present study, both CSCO and CS measures were analyzed to study the impact of imposing an additional requirement to maintain information about the serial order of commands. Although some differences emerged between the two measures, for the most part, they conveyed a consistent picture of performance. Although there may be theoretical reasons to consider both CSCO and CS measures, the CS measures are more appropriate within the context of aviation communication. Specifically, when ATC commands regarding heading, altitude, and speed are given to pilots, the order in which the commands are executed are under the pilot's discretion. Accordingly, the remainder of the summary will only address the effects surrounding the CS measure.

Regarding acknowledgement response, a verbal acknowledgement had the same

effect on speech and text formats regardless of message length because both formats use a verbal processing code as predicted by multiple-resource theory. The increase in length simply reduced verbal memory capacity as predicted by the working memory model. However, as predicted by multiple-resource theory, there was an advantage for a manual response because it uses separate resources from verbal information in memory and is processed in a different stage. More specifically, a manual acknowledgement was of greater benefit with longer text messages because text could be processed more efficiently than speech, given the same presentation times. However, due to the speed at which manual responses can be implemented with short messages and speech having direct access to the phonological store, a manual acknowledgement may invite more errors with text as compared to speech messages.

Regarding the effects of interference type and timing, CE interference reduced performance more than verbal interference because it disrupts rehearsal, and possibly encoding. This result suggests that more processing resources are required under CE interference which is consistent with the predictions of the working memory model. With respect to timing, interference presented *before* an acknowledgement had a greater negative effect than when presented *after* acknowledgement because more resources are required with an increase in task switching. The effects of interference type and timing are further qualified by message length. Thus, interference timing will differentially affect the ability to retain information in memory as a result of processing an interference task as shown in Figure 10. In general, the executive processing required by the fuel calculation task will impair performance regardless of timing and memory capacity when compared to a no interference control condition. On the other hand, the additional verbal

processing required by the call sign task does not appear to affect performance until moderate levels of memory capacity are reached and at high levels of memory capacity when presented *before* an acknowledgement. Furthermore, these effects are exacerbated when messages are presented as text as opposed to speech. More specifically, the negative effects of CE interference were greater than those of verbal interference following the presentation of text as compared to speech messages. The differences between the types of interference decreased with a decrease in memory capacity. However, there was one exception. Both verbal and CE interference did not differ from one other in the speech condition when the interference tasks followed an acknowledgement. Furthermore, the magnitude of the differences was greater when interference was presented *before* acknowledgement as a consequence of increased resource utilization resulting from task switching.

Methodological Considerations

The primary findings from the present study showed that, in general, text commands were affected more by interference than speech commands; the effects of CE were more detrimental than verbal interference; interference prior to an acknowledgement reduced performance more than when it followed an acknowledgement; manual responses improved performance with longer messages; and longer messages decreased performance. However, there were some methodological considerations that may have contributed to the outcomes of this study.

First, there was a large number of trials for participants to complete in each session. As with many memory studies there is some concern regarding performance on the latter trials due to proactive interference. However, it unlikely that proactive

interference could have played a significant role in the present study given the evidence for practice effects noted above. Some effect of learning was demonstrated with more CSCO and CS in the second as compared to the first experimental session. Given that performance improved over sessions, it is unlikely that stimuli from earlier trials impaired performance on subsequent trials.

Second, the presence of practice effects clearly shows that participants did not receive enough training prior to their first session. Although it would have been beneficial to provide more practice, it was not possible given the time constraints for participants in this study. In the future, additional time should be built into the experimental design so that performance can become stable prior to data collection.

Third, regarding the interference tasks, the CE task (i.e., fuel calculation task) may have been more difficult than the verbal task (i.e., call sign task) at the outset. Evidence of interference task difficulty was provided by the postexperimental questionnaire where fewer participants indicated they were able to use rehearsal as a strategy during the CE as compared to the verbal interference task. Consequently, the inability to rehearse under CE interference had a more pronounced and negative effect on control setting performance. Of note, there were instances where the verbal and CE interference tasks had equal negative effects on performance. First, recall that there were no differences between verbal and CE interference when presented after acknowledgement in the speech condition as shown in Figure 10. Second, there were no differences between interference types with a 3-command message in either format. Therefore, it could also be argued that the greater negative effects of CE as compared to verbal interference may be due to the experimental manipulations and not task difficulty.

Ideally, one should match interference tasks on difficulty a priori by equating single-task performance on each of the interference tasks. However, due to the nature of executive processing it could also be argued that there is an inherent difficultly associated with executive processing and that equating the difficulty levels across interference tasks would artificially reduce executive processing requirements. On the other hand, it is possible that the difficulty of the verbal task could be increased to match the difficulty of the CE task. Therefore, a future study should consider modifying either the CE or verbal task to make difficulty levels equal.

Fourth, and as mentioned in the results, the response time measure was confounded by acknowledgement response, interference timing, and message length because the measure captured the total time to complete each trial. The type of acknowledgement response affected response time because a manual button push response always required less time to execute than a verbal readback of the commands. Additionally, the control condition with no interference always required less time than when interference was presented before and after an acknowledgement. Further, shorter messages always took less time to present and acknowledge than longer messages. A decision was made a priori to record response time for a complete trial as a gross measure of comparison between formats with different acknowledgement responses; however, because of the experimental control to equate the two acknowledgement response times for each command length, it created a less reliable measure than expected. Recall, that the time allotted to acknowledge a message was dependent on message length and was held constant for both a verbal and a manual acknowledgement. Therefore, a more

appropriate measure of response time would have included only the time required to set the controls at the end of the trial as opposed to the entire length of a trial.

Fifth, anecdotal evidence from observing how participants dealt with verbal acknowledgements revealed that they occasionally took a few seconds longer than the allotted time to read back longer messages. In other words, as message length increased, occasionally there was also an increase in the amount of time needed to complete the verbal acknowledgement. This was only a concern when a verbal acknowledgement was required prior to an interference task because the additional few seconds of readback would overlap with and reduce the amount of time spent processing the interference task. On the other hand, it was not a concern when a verbal acknowledgement was presented after an interference task because any additional readback would only overlap with setting the controls. Thus, on some trials with longer messages, participants were still speaking when the interference task was presented. Therefore, there were negative effects associated with a verbal acknowledgement and longer messages on the interference task performance measures. It should be noted, however, that a decision was made a priori to maintain the integrity of the timing within the study such that the allotted time to acknowledge a message was the same as length of time required to present the message. This potential for the participant's response to overlap with the presentation of the interference task was addressed in the methodology by providing an auditory cue to alert participants to stop speaking and to begin the interference task. Although the auditory cues did not completely eliminate this problem, a possible solution for future research with verbal acknowledgements would be to allow more time for readbacks.

Theoretical Considerations

Most of the results from the present study can be interpreted within the framework of Baddeley and Hitch's (1974) working memory model and Wickens' (1984; 1991b) multiple-resource theory. However, there are limitations to these theories that do not address some aspects of the present study. First, the working memory model does not account for differences in the response stage of processing. For example, verbal acknowledgements were not as disruptive as expected. As previously discussed, a verbal acknowledgement is a confirmation of similar information in memory which is different from a verbal interference task that requires dissimilar verbal resources. Thus, the context of the information is important to consider, not just the verbal code. On the other hand, multiple-resource theory does suggest that there will be less competition among resources when different stages of processing are used. Second, because multiple-resource theory does account for different processing stages, a finer distinction between stages of communication can be made with regard to task switching. Although the original working memory model (1974) does not account for processing separate tasks in an alternating sequence, Baddeley (2001) does make assumptions concerning the use of both CE and verbal resources during task switching. Verbal resources are required to maintain the cognitive programs or instructions for the separate tasks while CE resources are necessary to shift attention and switch tasks. Thus, there should be no differential effects of CE and verbal interference with increases in task switching, because both CE and verbal resources are involved in task switching. However, performance differences were observed in the present study, that is, CE was more detrimental than verbal interference when more task switching was required. This finding suggests that the role

of the central executive processor may be more important than originally thought for task switching. Furthermore, multiple-resource theory does not make any assumptions regarding executive control. Thus, the effects of higher-order processes may be unaccounted for when the interpretation is limited to verbal or spatial categories. Therefore, in agreement with Baddeley, the processing of separate tasks in an alternating sequence (i.e., task switching) assumes that an executive controller is required to switch tasks and possibly manage and distribute the resources required by each task. The present study demonstrates that there is a need for a model of information processing that makes a finer distinction among processing stages and resources as offered by multiple-resource theory, but also includes an executive component that can manage those resources when tasks are processed sequentially over a period of time.

Implications

The results from the present study can be interpreted within the context of communication on the flight deck. The negative effects of CE interference suggest that pilots should avoid executive processing (i.e., higher-order mental operations) until communications with ATC are completed. Further, utilizing executive resources prior to the acknowledgement of an ATC instruction may reduce the likelihood that the command will be executed correctly. For instance, when ATC requests a change in flight plans because of weather, communications with ATC should be completed before making an assessment about the weather (assuming weather assessment requires executive resources). Yet, if the message contained only a single command, there would be no disadvantage to performing a verbal task (e.g., listening to additional radio information) prior to the execution of the command. This example illustrates the need to exercise

caution when coordinating multiple tasks in sequence because the order of the tasks and the type of processing code can impact memory for ATC information and ultimately performance. However, as the length of the ATC message increases, the processing code required by additional tasks and presentation format become less important because processing resources begin to reach capacity. Thus, it is important to distribute tasks so as not to overburden processing resources.

To illustrate further, reconsider the example noted earlier surrounding the ASRS report, ACN 561950. During a climb to FL370, the pilots became concerned about storms ahead. They contacted ATC for a minor route change and ATC requested they change altitude to FL330. Neither the captain nor the first officer reset the altitude to FL330. The first officer, who was flying, did not hear the amended altitude clearance and therefore did not repeat the information to the pilot per flight crew procedures. They attributed this error to distraction. They were focusing on the new route clearance, entering information into the flight management computer, and monitoring their distance from the storms (ASRS, 2003).

In this incident, the pilots were using executive resources to interpret the new clearance and to evaluate the weather situation in relation to their aircraft. More important, these executive resources were utilized immediately after ATC requested the change in altitude. The pilots labeled the cause of the error a "distraction". Given the results of the present study, one could argue the use of executive resources disrupted the rehearsal and possibly the encoding of the message. This example highlights the need to understand the role of timing and type of interference during the communication process.

Results from the present study also demonstrated that text is more susceptible to

the effects of interference type and timing. This would imply a greater concern for processing datalink messages. However, the permanence of datalink messages can overcome the memory resource problem. In a datalink system, the message is read exactly as sent and is always available because it can be stored. Therefore, in the context of aviation communication, memory for textual information may be of less concern. The storage aspect of datalink does not preclude the need to investigate text processing because there may be instances when datalink messages or portions thereof must be committed to memory. For instance, the datalink system has the capability to display messages on multiple pages. Thus, when a pilot is navigating a multipage message it may be necessary to retain information from a previous page in memory. Furthermore, there is the additional concern surrounding head-down time in a datalink environment caused by the need for pilots to navigate the menu system on the CDU instead of looking out of the window. Thus, pilots may attempt to remember information from the datalink system to minimize their head-down time.

Regarding acknowledgement response, the present study demonstrated that longer datalink messages should be acknowledged by a manual button press on the CDU. However, datalink will coexist with the current radio communication system. Therefore, there will be different modes of communication required for responding using two formats. At present, it is expected that the voice communication will be used for unusual and or urgent requests whereas datalink will be used for routine requests (Kerns, 1991; Van Gent, 1995). Therefore, it may be possible that a datalink message could be acknowledged with a verbal readback if both datalink and voice are used together. For instance, if a routine request was sent via datalink, but an urgent clarification was

required, then the acknowledgement of the datalink message may be in the form of a verbal readback. In the present study, there were no differences between speech and text formats with a verbal acknowledgement because both formats use similar processing codes. Therefore, one might not expect to see problems associated with acknowledging a datalink message verbally. However, in the present study, there was only a limited opportunity to examine messages crossed with acknowledgement responses over communication mediums. This issue was studied by Dunbar, McGann, Mackintosh, and Lozito (2001) who used both voice and datalink. They observed longer transaction times and more voice clarifications in a mixed environment compared to a voice only environment. In addition, the flight crews in their study made more errors entering ATC clearances in the mixed environment compared to voice or datalink alone. The results of Dunbar et al. suggest that individuals may have had difficulty in switching tasks and shifting attention between the two communication mediums. Therefore, the prioritization of tasks in a mixed environment is of concern and requires further examination.

Although datalink has inherent time delays because of the time required to generate, send, and acknowledge messages, those delays have been used advantageously to carry out other tasks (Lozito et al., 1993). Similarly, it has been shown that ATC controllers utilize the same time delays with datalink to distribute and optimize their workload without losing efficiency (Prinzo, 2001). Thus, another potential problem with datalink may be the introduction of time delays in an environment where timing can be critical. However, the potential problems caused by time delays must be viewed within the context of distributed workload, higher accuracy, and fewer total transmissions.

The opportunity to distribute workload by switching tasks with datalink is

advantageous and made possible because messages can be stored permanently. Such task switching in a voice environment where memory is required would most likely have negative effects similar to those observed in the present study. For instance, with increased task switching, the type of interference task and message length reduced resource capacity and the ability to rehearse commands. Thus, the effects of task switching in a voice environment would probably reduce the amount of information exchanged between ATC and the pilot because memory for speech information may be disrupted by additional task processing. Therefore, an increase in the number of transactions may be needed to clarify the information thereby reducing the efficiency of the communication process.

Communication efficiency can be considered an index of the number of transactions in a given period of time required to communicate a specified amount of information that is understood by the receiver. For example, communication between pilots and ATC would be considered more efficient when fewer clarifications are required. In reference to the present study, such an index may also be moderated by interference task type and timing factors. Efficiency will likely be reduced by interference prior to an acknowledgment because more transactions with ATC will be required to clarify information. For example, communication efficiency is reduced when a pilot fails to read back acknowledgements. In this instance, the number of transactions needed to communicate the same amount of information increases because ATC must repeat unacknowledged messages (Morrow et al., 1993). However, in a datalink environment, messages can be read exactly as sent and there is no verbal readback requirement: only button presses are required to downlink an acknowledgement to ATC.

Thus, there are fewer overall transactions with datalink as compared to voice because fewer clarifications are needed (Talotta & Shingledecker, 1992a, 1992b). Therefore, with regard to the effects of task switching, datalink communication may be more efficient because it can reduce the number of transactions.

As previously stated, the present study demonstrated that pilots need to consider task prioritization given the negative effects of task switching and the importance of processing codes required by the additional tasks. The results from the present study may have implications for other pilot responsibilities such as task management. Thus, a future direction for research could address how to facilitate performance by managing tasks in the context of task switching and task interference. Task management refers to the process used by flight crews to initiate, monitor, prioritize, and execute multiple tasks (Funk, 1991). For example, the concept of task management, which takes into consideration the priority of different tasks, can be applied to pilots completing procedural checklists. Such checklists are used to ensure that procedures are carried out in specific sequences in order to maintain safety (i.e., take-off and landing). These checklists may also require an additional step for the pilot to communicate with and integrate information from ATC. Therefore, if steps in the checklists require information to be read and retained from a cockpit display while sequentially processing ATC information, then understanding the resources required by each task in the checklist is critical to the proper execution of the procedure. For example, the crash of a Northwest plane in 1987 was the result of missed checklist item. The flight crew stopped processing their checklist prior to take-off to attend to an ATC request for a runway change. After changing runways, they resumed the checklist operations beyond the point where they

had originally stopped. The flight crew missed setting the flaps properly for take-off and crashed (Wickens, 2003). In this example, two findings from the present study are relevant: the negative effects of task switching and CE interference. First, there was an increase in task switching as a result of processing checklist items, communicating with ATC, changing runways, and then resuming checklist operations on the new runway. Thus, switching tasks in the middle of processing a checklist possibly interfered with and disrupted memory for the checklist items already completed and those that still required completion. Second, it is also likely that executive resources were used to coordinate the sequence of tasks and process the change in runway information. Therefore, interference from executive processing may have also disrupted memory for the checklist items that still required attention.

Furthermore, checklists are moving to an electronic format that will be displayed in the cockpit. Consistent with the present study and with regard to task switching, it has been observed that switching between paper checklists can cause items to be skipped and forgotten (Degani & Wiener, 1990). However, an electronic checklist would provide an opportunity for a dynamic and adaptable checklist system that could take into account tasks that have been completed and tasks that still require completion in accordance with the goals of the checklist. For example, to facilitate task switching in this context, the checklist could be designed to present the pilot with a cue to facilitate an attentional shift to the next task (Baddeley et al., 2001). Similarly, the checklist could provide partial information about a pending task which has been shown to help coordinate multiple activities more efficiently (Ho, Nikolic, & Sarter, 2001). In other words, an automated checklist system could be designed to improve the resource capacity of the user by

dynamically presenting tasks requiring separate resources in the appropriate sequence.

Conclusions

The introduction of datalink changes the nature of communication because it requires the processing of text as opposed to speech information and requires a manual as opposed to a verbal acknowledgement response. Further, the time delays inherent in a datalink environment provide opportunity for interference at different stages of the communication process. Previous studies have investigated the differences between speech and text processing with various types of interference (Risser et al., 2002, 2003, 2004; Scerbo et al., 2003). However, these studies did not address entire communication process from message reception to its execution; thus, the issues surrounding the timing of interference and the methods of responding were not addressed. Therefore, the present study was specifically designed to address the concerns regarding the timing of the interference tasks and the type of acknowledgement response on command execution performance. It was determined that executive processing has a greater negative effect on performance than verbal processing. However, these differences are reduced when there is more information in memory. Furthermore, there is a cost associated with switching tasks because more resources are required to shift attention between separate tasks. Therefore, carry-over effects are likely to occur between processing stages and more so as resources begin to reach capacity. Although performance was affected by interference type and timing, the impact was less dramatic for acknowledgement response. The results showed that the processing code used for a task had a larger effect on resource capacity than the response code. It can be concluded that more resources are used to process a task than to respond and this was more evident with CE as compared to

verbal interference. In other words, the processing code is of greater importance than the response code. Therefore, pilots must consider the type of information being processed and the order in which it is processed to maintain the integrity of the instructions in memory. This may be more of a concern with datalink because time delays allow pilots and controllers to distribute their workload and complete other tasks during communication. In addition, text appears to be more susceptible to the effects of interference as resources begin to reach capacity. Thus, the efficiency of communication can be moderated by these interference and timing factors and may ultimately affect the execution of commands. Collectively, the findings of the present study provide insight into the complex nature of information processing and ATC to pilot communication offering a perspective on the human memory capacity limitations and potential opportunities for human error.

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APPENDIX A

COMMAND LIST

Control	Values
Heading	5 to 360
Speed	220 to 480
Altitude	12,000 to 27,000

1-COMMAND MESSAGE SET

Message	Block	Sub-Command	Command
1	1	1	Set heading 040
2	1	1	Change speed 225
3	1	1	Change altitude 13900
4	1	1	Set speed 240
5	1	1	Change heading 075
6	1	1	Set altitude 24800
7	1	1	Change altitude 18500
8	1	1	Set heading 155
9	1	1	Set speed 460
10	1	1	Change speed 290
11	1	1	Set altitude 22100
12	1	1	Change heading 320
13	2	1	Change speed 325
14	2	1	Set heading 085
15	2	1	Set altitude 19400
16	2	1	Change altitude 12500
17	2	1	Set heading 150
18	2	1	Set speed 295
19	2	1	Change heading 050
20	2	1	Change altitude 14100
21	2	1	Set speed 390
22	2	1	Change speed 335
23	2	1	Set altitude 20700
24	2	1	Change heading 340

2-COMMAND MESSAGE SET

Message	Block	Sub-Command	Command
25	1	1	Change speed 340
25	1	2	Set altitude 20100
26	1	1	Set altitude 25700
26	1	2	Change heading 105
27	1	1	Change heading 110
27	1	2	Change speed 260

APPENDIX A (Continued)

Message	Block	Sub-Command	Command
28	1	1	Set altitude 19800
28	1	2	Set speed 245
29	1	1	Set speed 470
29	1	2	Change heading 200
30	1	1	Change heading 285
30	1	2	Change altitude 18100
31	1	1	Change heading 100
31	1	2	Set speed 275
32	1	1	Set heading 300
32	1	2	Set altitude 15900
33	1	1	Change speed 400
33	1	2	Set altitude 18900
34	1	1	Set speed 330
34	1	2	Set heading 220
35	1	1	Set altitude 25000
35	1	2	Change heading 125
36	1	1	Change altitude 22400
36	1	2	Change speed 370
37	2	1	Set speed 435
37	2	2	Set altitude 22200
38	2	1	Change heading 250
38	2	2	Set altitude 22800
39	2	1	Set heading 135
39	2	2	Change speed 280
40	2	1	Change altitude 21100
40	2	2	Change speed 265
41	2	1	Set altitude 14400
41	2	2	Change heading 230
42	2	1	Change speed 415
42	2	2	Set heading 195
43	2	1	Set altitude 12300
43	2	2	Set speed 300
44	2	1	Change altitude 25500
44	2	2	Change heading 090
45	2	1	Set speed 255
45	2	2	Change heading 130
46	2	1	Change speed 440
46	2	2	Set altitude 16500
47	2	1	Set heading 175
47	2	2	Set altitude 12900
48	2	1	Change heading 270
48	2	2	Change speed 395

APPENDIX A (Continued)

3-COMMAND MESSAGE SET

Message	Block	Sub-Command	Command
49	1	1	Set speed 310
49	1	2	Change heading 120
49	1	3	Set altitude 13200
50	1	1	Change heading 310
50	1	2	Set altitude 23700
50	1	3	Set speed 465
51	1	1	Set speed 315
51	1	2	Set altitude 22600
51	1	3	Change heading 265
52	1	1	Change altitude 21600
52	1	2	Change heading 290
52	1	3	Set speed 365
53	1	1	Set heading 210
53	1	2	Change speed 455
53	1	3	Change altitude 24200
54	1	1	Change altitude 16700
54	1	2	Set speed 375
54	1	3	Change heading 185
55	1	1	Change heading 305
55	1	2	Change speed 380
55	1	3	Set altitude 12400
56	1	1	Change speed 475
56	1	2	Set altitude 14800
56	1	3	Set heading 280
57	1	1	Set altitude 19100
57	1	2	Change speed 345
57	1	3	Set heading 225
58	1	1	Set speed 450
58	1	2	Change heading 160
58	1	3	Change altitude 24600
59	1	1	Change altitude 23800
59	1	2	Set heading 190
59	1	3	Change speed 305
60	1	1	Set heading 345
60	1	2	Set altitude 17600
60	1	3	Change speed 285
61	1	1	Set speed 410
61	1	2	Change altitude 24700
61	1	3	Set heading 240

APPENDIX A (Continued)

Message	Block	Sub-Command	Command
62	2	1	Change altitude 23200
62	2	2	Change speed 320
62	2	3	Set heading 070
63	2	1	Change speed 250
63	2	2	Set heading 045
63	2	3	Set altitude 19000
64	2	1	Change heading 330
64	2	2	Set altitude 20200
64	2	3	Change speed 360
65	2	1	Set altitude 25600
65	2	2	Set heading 180
65	2	3	Change speed 270
66	2	1	Set heading 360
66	2	2	Change speed 355
66	2	3	Change altitude 17500
67	2	1	Change heading 055
67	2	2	Set speed 425
67	2	3	Set altitude 18400
68	2	1	Set altitude 26600
68	2	2	Change heading 255
68	2	3	Set speed 405
69	2	1	Change heading 165
69	2	2	Change altitude 13100
69	2	3	Set speed 430
70	2	1	Set speed 420
70	2	2	Change altitude 19600
70	2	3	Change heading 080
71	2	1	Change altitude 17900
71	2	2	Set speed 350
71	2	3	Change heading 215
72	2	1	Set speed 385
72	2	2	Set heading 025
72	2	3	Change altitude 23100

APPENDIX B

CALL SIGNS

	Session 1	Session 2
Target		
1	*alpha-four*	*delta-eight*
Similar Distractor		
1	four-alpha	eight-delta
Similar Distractors		
1	alpha-one	delta-one
2	alpha-two	delta-two
3	alpha-three	delta-three
4	alpha-five	delta-four
5	alpha-six	delta-five
6	alpha-seven	delta-six
7	alpha-eight	delta-seven
8	alpha-niner	delta-niner
9	alpha-zero	delta-zero
Similar Distractors		
1	charlie-four	charlie-eight
2	foxtrot-four	foxtrot-eight
3	victor-four	victor-eight
4	echo-four	echo-eight
5	romeo-four	romeo-eight
6	sierra-four	sierra-eight
7	tango-four	tango-eight
8	india-four	india-eight
9	juliet-four	juliet-eight
Dissimilar Distractors		
1	bravo-one	bravo-four
2	delta-eight	alpha-one
3	golf-seven	golf-seven
4	hotel-niner	hotel-niner
5	kilo-two	kilo-two
6	lima-seven	lima-seven
7	mike-three	mike-three
8	november-six	november-six
9	oscar-five	oscar-five
10	papa-zero	papa-zero

APPENDIX B (Continued)

11	quebec-one	quebec-one
12	uniform-niner	uniform-niner
13	whiskey-two	whiskey-two
14	xray-five	xray-five
15	yankee-eight	yankee-four
16	zulu-three	zulu-three
17	charlie-six	charlie-six
18	foxtrot-seven	foxtrot-seven
19	victor-zero	victor-zero
20	echo-one	echo-one
21	romeo-eight	romeo-four
22	sierra-three	sierra-three
23	tango-six	tango-six
24	india-five	india-five
25	juliet-two	juliet-two
26	zulu-niner	zulu-niner
27	victor-zero	victor-zero

APPENDIX C

COUNTERBALANCE SHEET

	SESSION 1			SESSION 2		
Sub	**Format**	**Int**	**Response**	**Format**	**Int**	**Response**
01	Text	CE-VB	M-V	Speech	CE-VB	M-V
02	**Speech**	**CE-VB**	**M-V**	**Text**	**CE-VB**	**M-V**
03	Text	CE-VB	V-M	Speech	CE-VB	V-M
04	**Speech**	**CE-VB**	**V-M**	**Text**	**CE-VB**	**V-M**
05	Text	VB-CE	M-V	Speech	VB-CE	M-V
06	**Speech**	**VB-CE**	**M-V**	**Text**	**VB-CE**	**M-V**
07	Text	VB-CE	V-M	Speech	VB-CE	V-M
08	**Speech**	**VB-CE**	**V-M**	**Text**	**VB-CE**	**V-M**
09	Text	CE-VB	M-V	Speech	CE-VB	M-V
10	**Speech**	**CE-VB**	**M-V**	**Text**	**CE-VB**	**M-V**
11	Text	CE-VB	V-M	Speech	CE-VB	V-M
12	**Speech**	**CE-VB**	**V-M**	**Text**	**CE-VB**	**V-M**
13	Text	VB-CE	M-V	Speech	VB-CE	M-V
14	**Speech**	**VB-CE**	**M-V**	**Text**	**VB-CE**	**M-V**
15	Text	VB-CE	V-M	Speech	VB-CE	V-M
16	**Speech**	**VB-CE**	**V-M**	**Text**	**VB-CE**	**V-M**
17	Text	CE-VB	M-V	Speech	CE-VB	M-V
18	**Speech**	**CE-VB**	**M-V**	**Text**	**CE-VB**	**M-V**
19	Text	CE-VB	V-M	Speech	CE-VB	V-M
20	**Speech**	**CE-VB**	**V-M**	**Text**	**CE-VB**	**V-M**
21	Text	VB-CE	M-V	Speech	VB-CE	M-V
22	**Speech**	**VB-CE**	**M-V**	**Text**	**VB-CE**	**M-V**
23	Text	VB-CE	V-M	Speech	VB-CE	V-M
24	**Speech**	**VB-CE**	**V-M**	**Text**	**VB-CE**	**V-M**
25	Text	CE-VB	M-V	Speech	CE-VB	M-V
26	**Speech**	**CE-VB**	**M-V**	**Text**	**CE-VB**	**M-V**
27	Text	CE-VB	V-M	Speech	CE-VB	V-M
28	**Speech**	**CE-VB**	**V-M**	**Text**	**CE-VB**	**V-M**
29	Text	VB-CE	M-V	Speech	VB-CE	M-V
30	**Speech**	**VB-CE**	**M-V**	**Text**	**VB-CE**	**M-V**
31	Text	VB-CE	V-M	Speech	VB-CE	V-M
32	**Speech**	**VB-CE**	**V-M**	**Text**	**VB-CE**	**V-M**

APPENDIX D

STRATEGY QUESTIONNAIRE

For the fuel calculation task, we would like to know what strategy you used to perform the calculation. Did you *mostly*:

1. Only look at the numbers, and then add, subtract, or multiply the numbers as you would a typical math problem? (i.e., 150,000 – (10,000 + 10,000) = x)

   YES NO

2. Picture or imagine the level of fuel in the tank and the amount of fuel flowing to each engine to solve the problem?

   YES NO

3. Read to yourself each description of the value and then the value (i.e. "Fuel Flow 1 is 10,000"). Then, repeat the different components of the problem in your head as if it were a word problem in math? (i.e., "Subtract Fuel flow 1 plus Fuel flow 2 from total fuel")

   YES NO

For the tasks that you just completed, we would like to know if you used rehearsal (repeating the commands to yourself) or other strategies to keep the commands in memory. Answer these questions with regard to each of the tasks.

Did you use rehearsal (repeating commands to yourself) to remember the commands while you:

1. Performed the call sign task: YES NO

   If no, please describe the strategy used:

   ____

2. Performed the fuel calculation task: YES NO

   If no, please describe the strategy used:

   ____

VITA

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EDUCATION

Ph.D. - Industrial/Organizational Psychology, *December 2004*
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SELECTED PAPERS AND CONFERENCE PROCEEDINGS

Prinzėl, L.J., & Risser, M.R. (2004). *Head-Up Displays and Attention Capture* (No. NASA/TM-2004-213000). Hampton, VA: NASA Langley Research Center.

Risser, M.R., Scerbo, M.W., Baldwin, C.L., and McNamara, D.S. (2004). Implementing voice and datalink commands under task Interference during simulated flight. In D. Vincenzi, M. Mouloua, and P. Hancock (Eds.), *Human Performance, Situation Awareness, and Automation Technology Conference (HPSAA II): Vol. I. Current Research and Trends*, (pp. 201-206). Mahwah, NJ: Lawrence Erlbaum

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1999 Sentara Healthcare Excellence Award for Professional Development
1999 Sleep Research Society Excellence Award

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APA Division 21: Applied Experimental and Engineering Psychology *(1998)*
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