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# *Task Demand and Response Error in a Simulated Air Traffic Control Task: Implications for Ab Initio Training*

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*Abstract*

*This study investigated the relationship between task demand and the occurrence of error in an experimental simulation, which represented dynamic En-Route air traffic control. Participants were trained to baseline performance in the air-traffic-control task and then were presented with a series of 12 challenging but realistic scenarios. These scenarios were scripted to create two cycles of three levels of task demand as represented by traffic count. Conflict opportunities were scripted into each level of traffic count of six conflicts per scenario. Errors of omission were found to be equally likely when traffic count decreased from a peak as during a peak itself. This empirical finding was consistent with real-world experiences as reported in testimonial accounts by professional air traffic controllers. Given the restricted number of participants and their relative inexperience, we consider the present work to be an initial window into a highly complex issue. Our present findings have implications for ab initio training of air traffic controllers and also relate to performance in all operational domains, which demand flawless response from process control agents.*

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## Introduction

The evolving complexity of human-machine systems has served to increase the demands placed upon its operator's limited capacity to process information (see Rochester & Komos, 1976; Smolensky & Stein, 1998). The fluctuating profile of task demand posed in dynamic environments can be expected to elicit a spectrum of behavioral, subjective, and physiological responses, which contribute to operator workload and performance (see Hancock, 1997; Melton, 1982). The increasing trend toward ever more complex technologies, which tax the human information processing system, makes it crucial to develop a thorough understanding of the relationship between task demand, the operator's response to that demand, and the subsequent outcome reflected in the on-going level of performance efficiency. The present study investigated these relationships through the specific and chosen use of a simulated air traffic control (ATC) environment, which permitted the careful quantitative manipulation of task demand level through control of the number of aircraft to be monitored. Since air traffic control represents a dynamic process in which there are explicitly defined operational errors (Greene, Muir, James, Gradwell & Greene, 1997; Hancock, 1997; Hopkin, 1995; Metzger & Parasuraman, 2001), it offers the opportunity to collect a wealth of response data making it an ideal setting for the empirical investigation of task demand and cognitive workload in a success-critical environment.

One of the significant and continuing problems in human performance assessment concerns the meaning of the term *workload*. Some researchers use the term workload to represent objective characteristics of externally based tasks, while others use the same term to represent the subjective experience of the individual placed in that environment (cf., Hancock & Meshkati, 1988; Stager & Hameluck, 1990; Stager, Hameluck & Jublis, 1989). It is evident that this usage as a property of both the operator and the operator's environment has led to a debilitating confusion. We here distinguish between workload as task demand (the external properties of the task independent of any individual) and the operator's response to that task demand, which is assuredly contingent upon the capabilities and skills of the individual so exposed. We suggest that the construct of workload is best defined as a subjective subset of an individual's response to task demand, being closely aligned with the notion of adaptation advanced by Hancock and Warm (1989). Given our representation of workload as a response of the exposed individual, we define *task demand* as a property of the environment itself. Clearly, in this division, the operator's workload response is contingent upon his or her appraisal of any immediate environment as presenting a *task* in the first place. Where such appraisal does not result in the perception of an immediate task to be resolved, no associated workload is experienced (Hancock & Chignell, 1988). Often this specification of a *task* is a result of a third-party arbiter who dictates exactly what that *task* is (Smith & Hancock, 1995). In this present experiment, we, the experimental team, imposed the task. In the real world, tasks arise from a myriad of necessities. In ATC, the controllers' task derives from the ultimate need to provide safe and efficient air transportation.

In a constantly changing task environment, there are often many different sources of information. This profile of information is rarely exactly repeated and for each situation is arguably unique (Hancock, Flach, Caird & Vicente, 1995; Hancock & Meshkati, 1988). Task demand is crucially dependent on the type and amount of task-relevant information presented, and information changes the operator's behavior. We illustrate this by examining the task demand in simulated air traffic control where operators seek to maintain at least the minimum legal separation between aircraft (see Smith, Scallen, Knecht & Hancock, 1998). The level of task demand is a complex function of not only the assimilation and evaluation of task-relevant information, but also of the need to execute a number of cognitive and physical behaviors. The cognitive behaviors include recognizing sources of information on both analog and alphanumeric displays and deciding to intervene (or not) by issuing commands to the pilot (Smith & Murphy, 2000; Smolensky & Stein, 1998). The physical behaviors include monitoring the display, verbally issuing commands to the pilot, handing off aircraft to adjacent sectors, and organizing flight strips (Hopkin, 1995). Sources of task-relevant information include display symbols for aircraft, their vectors and intent, flight strip identifiers for aircraft and their flight-plans, and verbal and written input from traffic management coordinators, from the national weather service, from adjacent sector controllers, and from pilots themselves (Smith & Mafera, 2000). In our simulation-experiment, all sources of information other than traffic count were held constant. The independent variable in the experimental scenarios - the increasing, peaking, and decreasing of traffic count – was therefore the only manipulation of task demand in our study.

We define *response to task demand* as the ensemble of mental actions, overt behaviors, and physiological responses that follow from the operator's interaction with his or her task environment in order to fulfill the goal of the task (Hancock & Desmond, 2001; Melton, McKenzie, Polis, Hoffman, & Saldivar, 1973; Melton, McKenzie, Polis, Funkhouser & Lampietro, 1971; Thackray, Bailey, & Touchstone, 1975; Wilson & Corlett, 1999). Both acceptable performance and error are part of the operator's response to task demand. Another natural measure is task-relevant communication. (Carlson, 1982; Chapanis, 1953; Hendy, 1998) Our measures, the occurrence of error and of task-relevant communication, are overt behavioral indicators of the operator's response to the levels of task demand posed by the experiment.

*Task Demand and the Occurrence of Errors*

Errors are the nemesis of process control agents working in a system like air traffic control that has a high potential for risk (Smith, Briggs, & Hancock, 1997). *Operational errors* occur whenever two aircraft under positive control violate each other's protected zone (a violation of the minimum separation) which is a compound criterion of 5 miles longitudinally and 1000 feet vertically (Rodgers & Nye, 1993). These formal operational errors are distinguished from the *true errors* of omission and/or of commission that necessarily precede them. Operational errors are viewed not as errors *per se* but as the product of true error at some earlier point in time. Some true errors are errors of omission: the controller failed to take action that would maintain separation. Other true errors are errors of commission: the controller instructed an aircraft to make a maneuver that directly led to an operational error.

Several previous studies have examined controllers' subjective appraisal of workload (light, moderate, or high) and the occurrence of operational errors (Arad, 1964; Kinney, Spahn & Amato, 1977; Redding, 1992; Rodgers & Nye, 1993; Rodgers, Mogford, & Mogford, 1998; Schmidt, 1976; Stager et al., 1989; Stager & Hameluck, 1990). A review of these relevant studies reveals two themes. First, operational errors tend to occur when traffic count is low to moderate (approximately eight aircraft in the sector). Second, when controllers are asked to subjectively rate traffic volume and workload at the time of the operational error, they also tend to rate it as low to moderate.

It is unclear; however, whether these findings reflect (1) a decreased tendency to make operational errors under high traffic conditions or (2) the lower frequency of high traffic conditions in general (Endsley & Rodgers, 1997). Additionally, it is unclear from these reports whether the true error (of omission or of commission or a combination of these two influences) occurred (A) in low and moderate traffic conditions or (B) earlier when the level of traffic was relatively high. In either case, it may have manifested as an operational error only later when traffic had decreased to a low or moderate level. This source of uncertainty in linking the spatio-temporal occurrence in true error to reported operational errors is a major concern, which we have termed *the phase delay dilemma*.

*The Phase Delay Dilemma*

Phase-delayed errors are common in dynamic environments (Smith et al., 1998). In the ATC domain, the time lag between a true error and the operational error poses a fundamental dilemma: How are we to know when the true error actually occurred? For example, suppose an operational error occurred during a peak in traffic count. Did the true error also occur during this peak or did it occur earlier as the level of traffic was increasing? Due to the phase delay dilemma, previous research into operational errors may not reveal the actual link between true errors and operational errors and between true errors and task demand. It is therefore not reasonable to conclude that an operational error is a function of a particular level of traffic when the relationship between the true errors and the level of task demand still remains uncertain.

Our experiment was designed to address this impasse by scripting air traffic scenarios that controlled for the phase delay dilemma and by obtaining behavioral measures of performance and response to task demand. Our premise is that systematically changing traffic count in realistic En Route air traffic scenarios result in systematic variations in task demand. By creating two peaks of traffic count in a scenario, we control for the potential confound of operator fatigue. By incorporating conflict opportunities within each level of traffic count, we also address the potential effects of phase-delayed operational errors and make it possible to distinguish between errors of omission and errors of commission.

## Experimental Method

### *Experimental Participants*

Three, upper level, undergraduate students volunteered to act as the air traffic controllers over a six-week period. A second trio of students acted as pseudo-pilots. Participants received class credit for their participation. All participants received 6 practice and 12 experimental scenarios over the six-week period. Scenarios were counterbalanced using a selection from a Latin Square. Students were used rather than professional air traffic controllers for two reasons. First, the purpose of the study was to observe and document errors and inexperienced participants are much more likely to make errors than professionals are. Second, recent national security events have made it extremely difficult to work with professional air traffic controllers (Hancock & Hart, 2002), although we would have preferred to do so. We are fully aware that inexperienced participants are inclined to make different errors than experienced participants (Reason, 1990). Therefore, our results may generalize most to novices like those undergoing ab initio training. However, in mitigation of such issues, at the present stage we are more concerned with contributing to basic empirical understanding than with the immediate domain-specific application of such knowledge.

### *Experimental Task*

The student-controllers were responsible for maintaining the Federal Aviation Administration's criterion for minimum separation between aircraft by issuing appropriate verbal commands to the pseudo-pilots. Command options included changing an airplane's heading, altitude, and/or speed. Pseudo-pilots provided verbal confirmation of controller commands and maneuvered their aircraft accordingly. Pseudo-pilots were trained along side the controllers and were instructed to complete the controller's commands as quickly and as accurately as possible. Analysis of scenario histories confirmed their accuracies in responding, which leads us to conclude that this element of the simulation did not influence subsequent results. During the two weeks of the practice session, the students learned how to use the experimental platform. They became adept at monitoring dynamic traffic, at identifying and resolving potential operational errors, and at giving and confirming verbal commands designed to maintain separation. The criterion for baseline performance was resolution of six scripted aircraft conflicts in a 30-minute practice scenario.

### *Experimental Platform*

The experiments were run using the Distributed Air Traffic Information Display Simulator (DATIDS), a full simulation of an ARTCC sector controller's workstation (Klinge, Smith, & Hancock, 1997). The simulator presents a representation of the composite radar screen, the computer read-out display, and the buttons and dials used to adjust the settings of the R-side ATC display and an illustration of this simulation is shown in Figure 1.

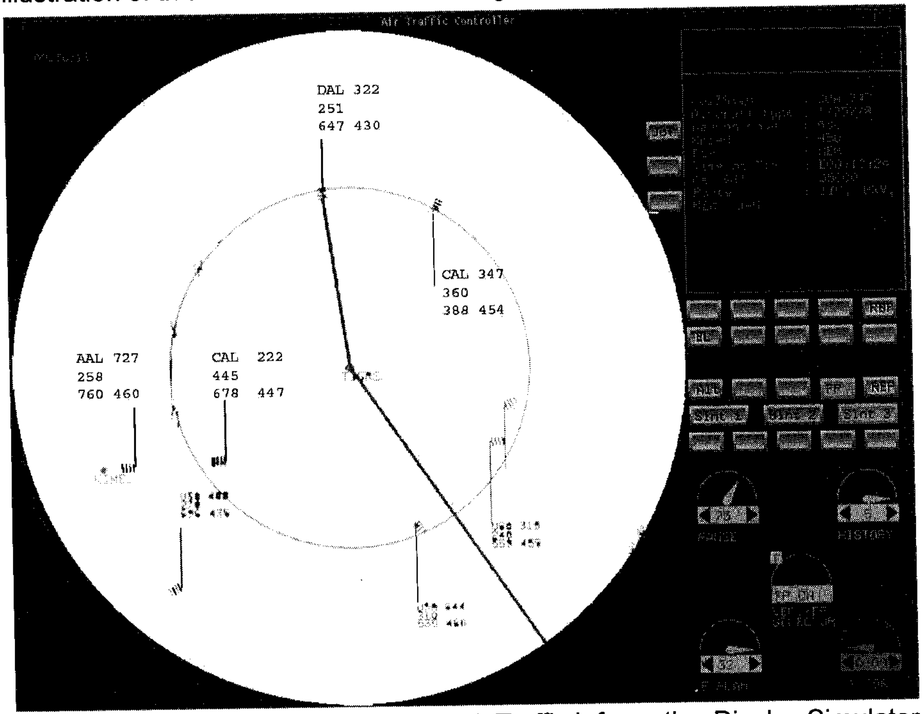


*Figure 1.* Illustration of the Distributed Air Traffic Information Display Simulator (DATIDS).

*Experimental Design*

As shown in Figure 2, the experimental scenarios incorporate two blocks of time, each containing a cyclic pattern of traffic count with three levels (5 minutes of increasing traffic, 5 minutes of peak traffic, and 5 minutes of decreasing traffic). The two 15-minute blocks and three levels of traffic count yield a 2x3 repeated measures design. The repeated blocks permit an assessment of the potential confound of fatigue. Task demand is operationally defined as the average traffic count, being the average number of aircraft visible on the controller's information display at each minute. More specifically, in the first period of five minutes of each block, the traffic count continually increased from three aircraft to a peak value of 16 aircraft. During the second period of five minutes of each block, the traffic count remained at or near this peak. In the third period of five minutes of each block, the traffic count gradually decreased until it returned to the baseline of three aircraft. These criteria, of a minimum of three aircraft and a maximum of 16 aircraft, were adopted based on actual observations of a controller's typical sector load (Smith & Murphy, 2000).

*Controlling for Phase Delay*

To make errors of omission evident, two aircraft were scripted to create two distinct opportunities for an error of omission in each of the six levels of traffic count. The two aircraft entered and exited the information display during the same (five minute long) level of traffic count. If the student-controller took no action to maneuver these aircraft, then the resulting operational error could be attributed to an error of omission that occurred during that level of traffic and not in a prior level. This control makes it possible to know the number of aircraft and the level of task demand when and if errors of omission occurred. All other aircraft were scripted to be conflict-free. Therefore, if any other errors occurred (at any time) they could be attributed to an error of commission.

*Dependent Measures*

The primary performance measure was the number of operational errors due to errors of omission or due to errors of commission occurring throughout the experiment. The behavioral measure of response to task demand was the number of commands between controller and the pseudo-pilot.

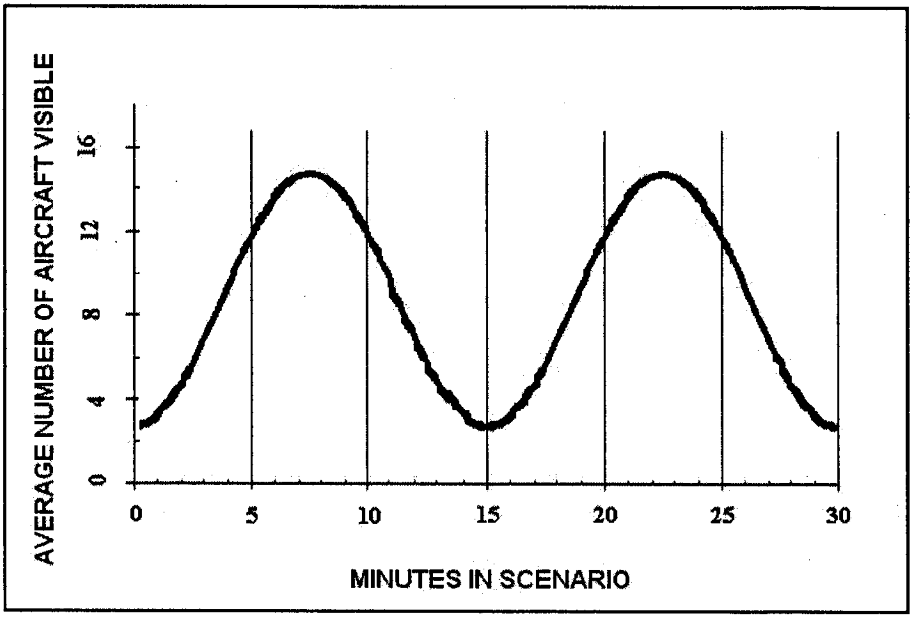


*Figure 2*. Illustration showing the schematic design of the experimental scenarios.

The horizontal axis is elapsed time in the scenario. The vertical axis is the minute-by-minute average number of aircraft visible on the controller's information display. Each scenario lasted 30 minutes and presented two cycles of traffic count. Each cycle contained three periods of five-minute-long conditions of traffic count: increasing, peak, and decreasing. In each cycle the average number of aircraft increased for a period of five minutes from a baseline of approximately three aircraft, remained near a peak level of approximately 16 aircraft for five minutes, and then decreased for a period of five minutes back to the base level. Opportunities for operational errors due to errors of omission were scripted into all six periods of five-minute-long conditions of traffic count.

## Experimental Results

A repeated measures 2x3 (two blocks of time by three levels of traffic count) analysis of variance was used to analyze the error and communication data. The number of scenarios (12) acted as a proxy for number of participants in order to increase the statistical power of the test. Mauchly's test of sphericity was not significant for any of the analyses and thus sphericity was uniformly assumed.

### *Errors of Omission*

Figure 3 shows the total number of errors of *omission* for each level of traffic count (increasing, peak, and decreasing) and both blocks of time. A 2x3 repeated measures ANOVA was conducted to determine the effect of traffic level and block of time on the number of operational errors due to errors of omission. The main effect for traffic level was found to be significant, $F(2, 22)=10.73, p<.001$. A within-subjects $eta^2=.50$ indicates a medium effect size for traffic level. Post-hoc pair-wise comparisons revealed no significant difference between the mean number of errors of omission in the peak and decreasing conditions. However, both the peak and decreasing conditions were significantly different from the increasing condition for both blocks of time, $p<.05$. It appears that the student-controllers were just as likely *not* to take corrective action to resolve potential conflicts after a peak in traffic as they were during a peak in traffic for both blocks of time in the scenario.

### *Errors of Commission*

Figure 4 shows the total number of errors of *commission* for each level of traffic count and both blocks of time. A 2x3 repeated measures ANOVA was conducted to determine the effect of traffic count (increasing, peak, and decreasing) and block of time on errors of commission. Traffic level was not found to be significant. However, there was a significant difference for blocks of time, $F(1, 11)=7.86, p<.01$. The within-subjects $eta^2 = .42$ indicates a medium effect size. While many more errors of commission were made in the second block than in the first block, the totals are low but remain significant. Errors of commission were relatively rare. They occurred when student-controllers issued inappropriate commands that caused an operational error between aircraft that otherwise would have remained separated. These results suggest that the student-controllers experienced some amount of fatigue or vigilance decrement (Mackworth, 1948; Mackworth, 1957; Hancock, 1984) or both.

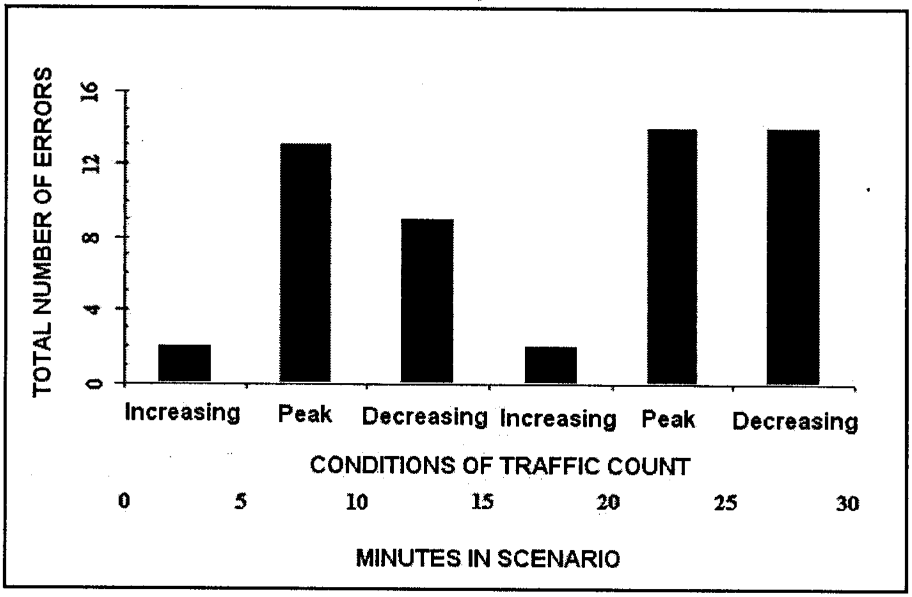


*Figure 3.* Total number of operational errors due to errors of *omission* collapsed across scenarios and conditions.

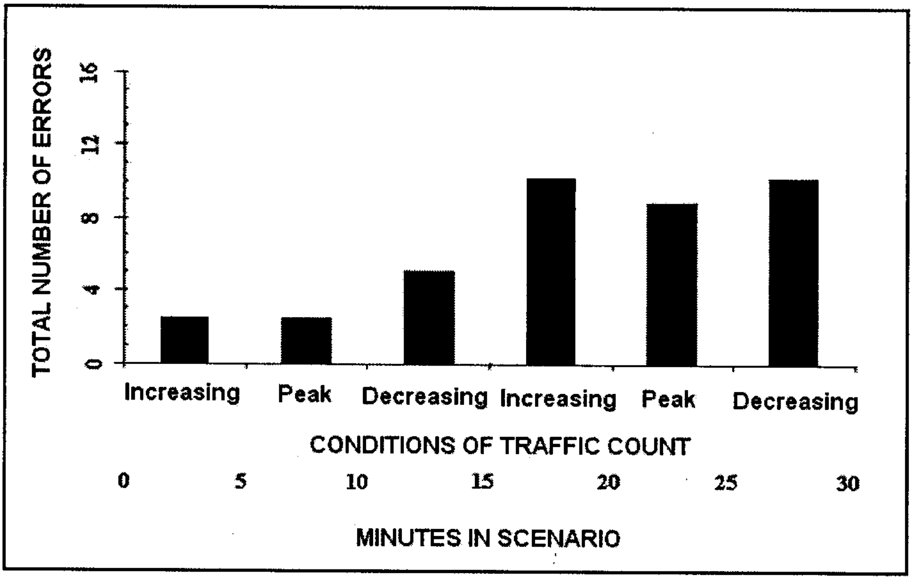


*Figure 4.* Total number of operational errors due to errors of *commission* collapsed across scenarios and conditions. The vertical scale is the same as in Figure 3 to facilitate comparison.

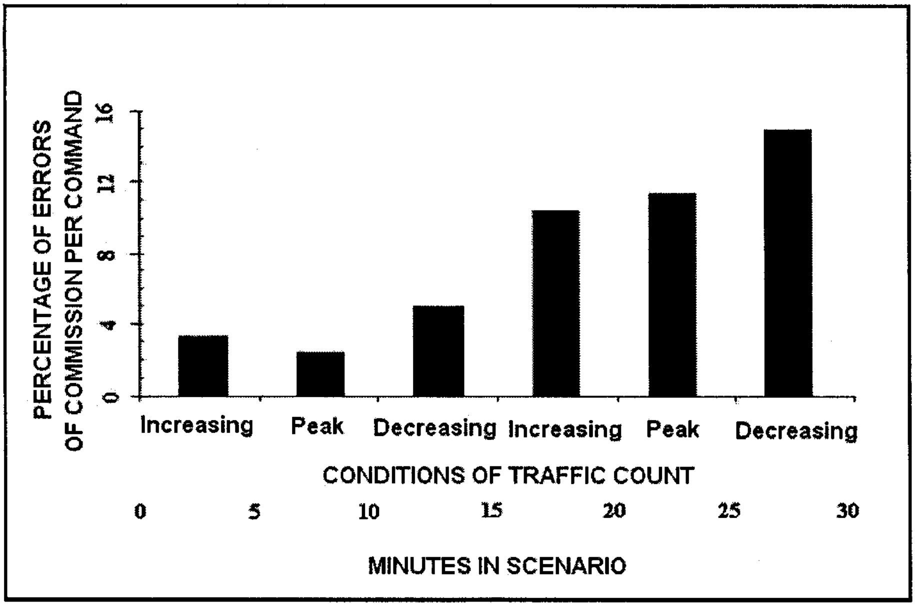


*Figure 5.* Percentage of errors of commission per command to maneuver aircraft issued by participants collapsed across scenarios and conditions.

*Controller Communication*

Figure 5 shows the percentage of errors of commission per command to aircraft issued by the student-controllers for each level of traffic count and both blocks of time. A 2x3 repeated measures ANOVA was conducted to determine the effect of traffic level and block of time on the communication. The interaction between the three levels of traffic and the two blocks of time was significant, $F(2, 22)=8.29$, $p<.002$. The within-subjects $eta^2 = .43$ indicates a medium effect size. The interaction suggests that the relationship between communication and errors of commission is such that more errors of commission are committed per command during the second block of time. This may be due to fatigue, diminished attention capacity, or both.

*Correlations*

A correlation analysis was conducted to detect emergent relationships between the dependent and independent variables. The analysis, shown in Table 1, found significant positive correlations between two of the three dependent variables, errors of omission and communication, and the experimental treatment, level of traffic count. These results indicate that the manipulation of traffic count had an effect on participant behavior. Both types of error were found to correlate significantly with communication. The correlation between communication and errors of commission was positive. This result suggests that errors of commission tended to occur during periods when the student-controllers' response to task demand was relatively high. In contrast, the correlation between communication and errors of omission was negative. This result suggests that inadvertent operational errors tended to occur when the student-controllers' response to task demand was relatively low.

Table 1
*Correlations between the three dependent variables - errors of omission, errors of commission, and communication – and the main dependent variable, traffic count.*

| | Omission | Commission | Communication | Traffic |
|---|---|---|---|---|
| **Omission** | 1.00 | 0.03 | -0.14 * | 0.21 ** |
| **Commission** | | 1.00 | 0.22 ** | -0.06 |
| **Communication** | | | 1.00 | 0.13 * |
| **Traffic** | | | | 1.00 |

*** Correlation is significant at the .05 level (2-tailed)**
**** Correlation is significant at the .01 level (2-tailed)**

## Discussion

The purpose of this study was to develop an understanding of the relationships between task demand, the operator's behavioral response to that demand, and the occurrence of errors of omission and of commission in a simulated ATC environment. The data suggest that errors of omission are equally likely to occur after a peak in task demand as during that peak and are associated with relatively low levels of response to task demand. Errors of commission are more likely to occur when response to task demand is unusually high and time-on-task has made it likely that fatigue has set in. In short, this type of error is sensitive to fatigue, to the level of task demand, and to the operator's behavioral response to that task demand. Previous investigations of task demand, response to task demand, and the occurrence of errors in the ATC domain (e.g., Kinney et al., 1977; Stager, Hameluck, & Jublis, 1989; Stager & Hameluck, 1990) has focused on workload, the operator's subjective response to task demand. Using archival data, they reported that operational errors were more likely to occur when workload was said to be moderate to low. Since the data were archival, these studies failed to control for the phase delay dilemma, the time lag between the operational error and the error of omission or commission that necessarily preceded them.

### *Errors of Omission*

The total number of errors of omission across conditions shown in Figure 3 revealed that operational errors due to errors of omission were equally likely to occur after a peak in traffic as during a peak. This finding was consistent with anecdotal evidence reported by professional air traffic controllers. Most controllers freely admit that operational errors occur most often on the backside of a peak in traffic. Unlike previous archival studies investigating operational errors, the current study scripted the simulated traffic scenarios to control for traffic phase-delay. Consequently, the current study contributed a new finding: operational errors occur equally as often on the backside of the peak in traffic as they do during the peak. These results were found for both blocks of time, beginning of scenario (first 15 min) and end of scenario (last 15 min), suggesting that operational errors due to errors of omission are more likely a function of task demand than of fatigue. If the effect were due to fatigue following high traffic levels, then significantly more errors would have occurred at the end of the scenarios, which was not the case. These findings suggested that the decrease of task demand after a peak is just as taxing on inexperienced participants as the peak itself. These participants were expending relatively high levels of effort as they made errors of omission. Operational errors due to omission were not often a result of the inexperienced participant dropping his or her guard.

The correlation between errors of omission and communication was negative in this experiment, see Table 1. Our inexperienced participants issued inappropriate commands to aircraft while missing critical cues about impending conflicts. It appears that the operational errors due to errors of omission in this experiment may reflect our participants' relative lack of skill. Accordingly, these present results may generalize only to inexperienced students in Collegiate Training Initiative institutions that are beginning their training to become air traffic controllers. Whether such results generalize to actual operations or other operations in other process control domains requires further empirical evaluation.

*Errors of Commission*

The number of errors of commission steadily increased as scenarios progressed, see Figure 4. This result suggested that operational errors due to errors of commission are more a function of fatigue than of the cyclic manipulation of task demand. Additional evidence of a fatigue effect was found in the statistically significant pattern of the errors of commission per command, shown in Figure 5. These findings were congruent with the vigilance literature, which reported that the frequency of correct detections tends to decrease after 20 minutes on watch (e.g., Hancock & Warm, 1989; Mackworth, 1948; Mackworth, 1957; Parasuraman, 1986; Warm, 1984). This deterioration in performance is traditionally termed the "vigilance decrement."

*Limitations of the Study and Future Directions*

The correlation data in Table 1 show that the cyclic manipulation of traffic was positively correlated with two of the dependent measures, communication and errors of omission. An analysis of variance found that the fluctuation of task demand had an effect on the participants' responses to task demand. These results suggested that this study had high internal validity. However, there are two significant threats to the external validity of this study. The first is nature and the small size of our sample – three participants, all of whom were undergraduate psychology students. However, these students were trained and participated in the study for over six weeks (two weeks of the practice session and four weeks of the experimental session). Therefore, the results may generalize primarily to inexperienced trainees striving to be air traffic controllers. Future studies should of course address a larger group of participants from a pool that is more representative of trainees. That said, it must be noted that Federal and union regulations make it extremely difficult to gain access to these FAA trainees. Eventually if the work is to exert a strong practical impact, it might be replicated and extended with full-time professional controllers. The second threat is construct validity. In debrief sessions none of the student-controllers mentioned the cyclic pattern of task demand and the relatively regular occurrence of the scripted conflicts. Nevertheless, it is possible that they were implicitly aware of them, made tacit hypotheses about them, and responded to those hypotheses. Construct validity may be improved by counterbalancing the order of the presentation of conditions (e.g. from {increase, peak, decrease} to {peak, decrease, increase} etc.), and by adding control conditions with uniform levels of task demand in order to get baselines of performance (see Hancock, Williams, Manning, & Miyake, 1995).

The major finding in this study was that errors of omission are equally as likely on the backside of a peak in task demand as during the peak. It would be useful to determine whether this finding generalizes to other process control and continuous operator tasks and other dynamic environments. Tasks and environments that are amenable to laboratory simulation include operating a motor vehicle, piloting an aircraft, firing weapons, and operating an assembly line. Such studies would be especially effective if the order of the presentation of levels of task demand was fully counterbalanced and control conditions used to get baselines of performance. For example, one useful control condition would pose scenarios with two cycles of traffic demand but no scripted conflicts. Other control conditions would pose scenarios with constant (but different) levels of traffic demand and several scripted conflicts. The resulting within-subject comparisons would provide a strong test of the generality of our results. If this preliminary finding of errors of omission on the backside of peaks in task demand holds up to further testing, it would become imperative to investigate ways of mitigating this effect. Eye tracking during the task could provide detailed information about the information the operator is focusing on (hits vs. noise) and might shed light on these sources of errors and, in turn, on ways these errors might be avoided.

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