Task Demand Variation in Air Traffic Control: Implications for Workload, Fatigue, and Performance

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Abstract. In air traffic control, task demand and workload have important implications for the safety and efficiency of air traffic, and remain dominant considerations. Within air traffic control, task demand is dynamic. However, research on demand transitions and associated controller perception and performance is limited. This study used an air traffic control simulation to investigate the effect of task demand transitions, and the direction of those transitions, on workload, fatigue and efficiency performance. A change in task demand appeared to affect both workload and fatigue ratings, although not necessarily performance. In addition, participants' workload and fatigue ratings in equivalent task demand periods appeared to change depending on the demand period preceding the time of the current ratings. Further research is needed to enhance understanding of demand transition and workload history effects on operator experience and performance, in both air traffic control and other safety-critical domains.

Keywords: Workload transitions · Workload history · Air traffic control · Fatigue · Time based metering · Task demand transitions

Introduction

Within the safety critical domain of air traffic control (ATC), workload "is still considered one of the most important single factors influencing operators' performance" [1 p639]. Workload has been defined within the ATC domain as the result of an interaction between task demand and the controllers' selected strategy [2]. The association of workload and controller performance has important implications for the safety and efficiency of air traffic (e.g. [3]; [4]). Workload therefore remains a dominant consideration.

In ATC, as with many other safety critical environments, task demand and workload are dynamic. Air traffic controllers (ATCOs) frequently experience changes in traffic load and the complexity of the traffic situation, potentially resulting in the experience of transitions between high and low workload. These transitions can be expected by the controller, such as when traffic load changes based on the time of day or known activities in surrounding sectors, or unexpected, for example, through increased complexity resulting from an emergency situation. Transitions may also be gradual or sudden [5].

Research on demand transitions, and the effect on both performance-influencing covariate factors (such as workload and fatigue) and task performance is limited however, with studies frequently utilizing a constant task demand or workload [6]. Of the research available, there appears to be conflicting findings. Some (e.g.[7]) have reported that overall performance efficiency on a vigilance task was not affected by task demand transitions, regardless of whether the transition was expected or unexpected. However, others (e.g. [8]) have found that performance on vigilance tasks was influenced by a low to high demand transition or high-to-low demand transition (e.g. [5]). Task demand and workload transition research specific to an ATC environment is particularly underrepresented. Consequently, there is limited understanding of the influence of workload transitions on performance in an air traffic environment.

The aim of this study was to investigate the influence of expected and gradual task demand transitions (high-low-high and low-high-low) on workload, fatigue and performance, within a high fidelity ATC simulation environment. Due to the quantity of measures and data generated from this study, only a subset of the measures and findings that are most relevant to the research aim are presented.

Method

Design

An en-route ATC human in the loop (HITL) simulation was utilized to investigate task demand variation on workload, fatigue, and performance. Efficiency-related performance was inferred from aircraft delay (in seconds) at a specific point in the arrival sequence (three nautical miles before the meter fix). Participants were eight ex-ATCOs who had previously worked in enroute airspace in Oakland Air Route Traffic Control Center (ARTCC). Pseudo pilots were paired with controllers, and completed standard pilot tasks such as controlling the aircraft in accordance with controller instructions and communicating with controllers. Participants operated a combined low and high altitude sector, and were assigned to meter aircraft into the northeast corner of the Phoenix Terminal Radar Approach Control (TRACON). This airspace was selected for the complex mix of arrivals and overflights.

The study used a within-measures design. The direction of the task demand transition was manipulated to create two scenarios. Scenario 1 followed a high-low-high task demand pattern and scenario two followed a low-high-low task demand pattern. The creation of three task demand periods was implemented in order to better reflect the multiple task demand transitions that can be experienced within an operational environment. In addition, this permitted an extension of previous studies that had focused on the comparison of workload and performance between one transition period (e.g. [5]). Each simulation session lasted for 90 minutes and consisted of three, 20 minute [9] periods of stable task demand which alternated between high and low, interspersed with a total of three, 10 minute transition phases. Task demand was created by the number of aircraft under control [10] as well as the ratio of arrival aircraft and overflights. Arrival aircraft create complexity in the task, which influences task demand. Task demand phases for equivalent stable task demand periods (i.e. high demand regardless of which scenario the high demand was positioned in) were created using the same aircraft counts and number of arrival aircraft, permitting comparability between demand variation scenarios. Scenarios followed a counterbalanced presentation. Participants were required to complete all control actions and meter aircraft to arrive at a meter fix at a scheduled time. Participants were provided with a 1 hour briefing prior to the start of the study, and six training runs (four 90 minute training runs and two 45 minute training runs).

Participants

A total of eight male ex-controllers took part in the simulation. Age ranged from 50 years – 64 years. Participants responded to grouped age ranges and so an average age could not be calculated. Participants had worked as en-route controllers in the Oakland, California, ARTCC. Participants' years of experience as active ATCOs (excluding training) ranged from 22 – 31 years (M=26.56, SD=3.90).

Measures and Apparatus

Covariate factors were measured using subjective, self-report scales. Mental workload was measured using the uni-dimensional Instantaneous Self-Assessment (ISA) scale which measures workload from 1-6 [11]. Every three minutes, participants were presented with the ISA rating scale at the top of the radar scope and asked to click on the workload rating. Fatigue was measured using the Samn-Perelli scale, which ranges from 1-7 with behavioral anchors at each point on the scale. [12]. Fatigue measures were taken three minutes into, and three minutes prior to the end of, each 20 minute task demand phase and six minutes into each 10 minute transition phase. This periodicity was selected to capture data across each stable task demand period, and refined based on results from three pilot studies. Performance was assessed by aircraft delay at three nautical miles from the meter fix point as a measure of participants' efficiency-related performance. An aircraft that is on-time, i.e. without delay, suggests optimal performance. An efficiency-related performance measure was selected for analysis as opposed to a safety-related performance measure as previous research suggests that controllers can maintain safety-related performance without significant observed changes even under high periods of demand by applying workload management strategies [13]. Changes in performance are frequently first observed in efficiency-related tasks (e.g. [13]). An efficiency-related task was therefore potentially more sensitive to changes in performance.

The software used was the Multi-Aircraft Control System (MACS) [14]. Participant workstations were configured with a BARCO large-format display and keyboard/trackball combination that emulates what is currently used in en-route air traffic control facilities. Voice communications between ATCOs (the participant and a non-participant controller controlling neighboring sectors) and the pilot were enabled via a custom, stand-alone system. Datalink communications were also available. Data were collected continuously through MACS's data collection processes.

Results

Analysis approach

Due to the quantity of analyses and findings, only the data trends most relevant to the research aims are presented in this paper. To address the research aim, comparisons of the three 20 minute task demand periods per scenario are presented in the following sections.

For each workload, fatigue and the dependent variable of aircraft delay in arrival, descriptive statistics were first reviewed, followed by further exploration through the application of two repeated measures ANOVAs – one for each task demand transition scenario (scenario 1: high-low-high demand; scenario 2: low-high-low demand). The decision to apply separate repeated measures one-way ANVOAs was made based on a review of previous research analysis approaches to similar experimental designs (e.g. [5]) and research aims. The research aim of this study focused on investigating the effect of task demand on covariate and performance variables, including the direction of the task demand. One way ANOVAs permitted the exploration of changes within each task demand scenario. Prior to all inferential statistics, data were checked for normality and sphericity violations. Unless otherwise reported, all data met these assumptions.

Task Demand Variation Manipulation Check

A review of the descriptive statistics suggests that task demand did vary in the intended direction (Fig.1). Figure 1 confirms that the number of aircraft in the controller's sector were similar between equivalent task demand periods regardless of scenario (high-low-high demand or low-high-low demand). The number of arriving aircraft was also similar.

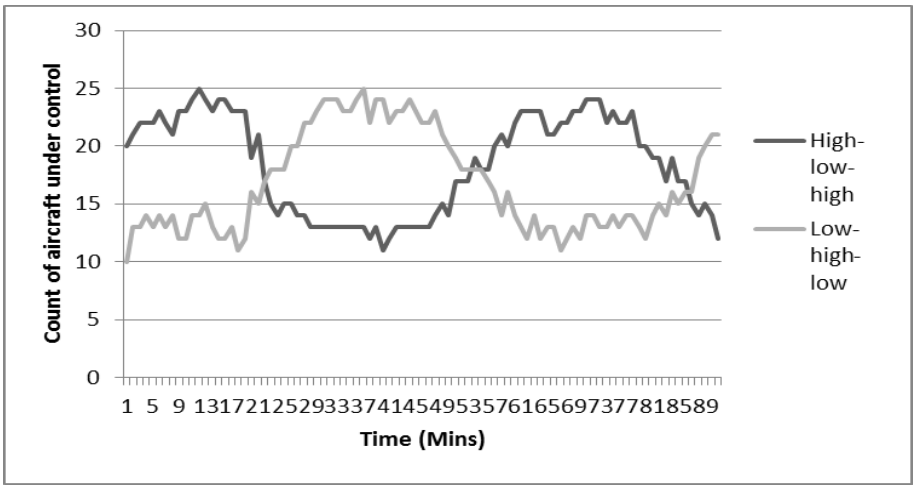

Fig. 1. Count of aircraft under control by minute for scenario 1 (*high-low-high demand*) and scenario 2 (low-*high-low demand*).

Task Demand and Subjectively Experienced Factors

Task Demand and Workload

Table 1. Mean and standard deviation for workload (as rated by ISA) in both scenario 1 and scenario 2, averaged across 20 minute task demand periods.

Workload (ISA)	Task demand period 1 (0-20 minutes)		Task demand period 2 (31-50 minutes)		Task demand period 3 (61-80 minutes)	
	M	SD	M	SD	M	SD
Scenario 1 workload (High-low-high)	3.67	0.77	2.87	0.61	3.85	0.62
Scenario 2 workload (Low-high-low)	2.78	0.64	4.06	0.71	3.33	0.61

Workload ratings were averaged across the 20 minute periods of stable task demand for analysis to facilitate comparison between the separate task demand periods. A review of the descriptive statistics (Table 1) suggest that workload in both scenarios varied as expected with task demand. In scenario 1 (high-low-high demand) workload appears to be rated slightly higher in the third task demand period (high demand) compared to the first task demand period (high demand). In scenario 2 (low-high-low demand), workload was rated highest in the high demand, second task demand phase. However, on average, participants rated perceived workload to increase in the third task demand period (low demand) compared to the first low demand period. Comparing between scenario 1 and 2, the high demand period is perceived to generate the most workload for participants in the low-high-low demand scenario, although the high demand periods were objectively equivalent between scenarios. Comparing across low demand periods between conditions, workload is rated similarly in the first period of scenario 2 and the middle period of scenario 1. However, the low demand period in the third period of scenario 2 is rated as higher workload than either of the other low demand periods.

To further examine the changes in perceived workload, a one-way repeated measures analysis of variance (ANOVA) was conducted for each scenario [5]. A one-way ANOVA was applied to each scenario, to explore differences within-scenarios. In relation to scenario 1 (high-low-high demand) a significant main effect of task demand period was found on self-reported workload $F(2,14) = 44.23$, $p<0.001$. Pair-wise comparisons revealed that workload was significantly lower in task demand period 2 (low demand) than high task demand period one ($p<0.005$) and three ($p<0.001$). Workload was not rated significantly differently between high demand period 1 and high demand period 3 ($p=0.68$). In scenario 2 (low-high-low demand) a significant main effect of task demand period was found on self-reported workload $F(2,14) = 32.72$, $p<0.001$. Pairwise comparisons revealed that workload was rated significantly higher in the high demand period than the first low demand period ($p<0.001$) and second low demand period ($p<0.005$). It was also identified that the workload ratings in the second low demand period were significantly higher than the first low demand period ($p<0.05$).

Task Demand and Fatigue

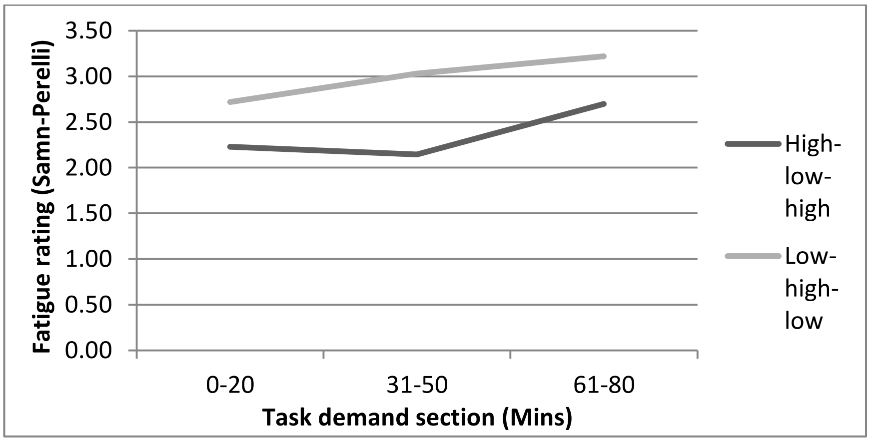

Fig. 2. Fatigue ratings (as measured by Samn-Perelli scale) averaged across 20 minute task demand periods for scenario 1 (*high-low-high demand*) and scenario 2 (*low-high-low demand*).

A review of the means of reported fatigue for each task demand period in scenario 1 (high-low-high demand) revealed that ratings of fatigue appeared similar between high demand period one (M=2.23, SD=0.71) and low demand period one (M=2.15, SD=0.77) (Fig. 2). Fatigue ratings were slightly higher in the third demand period, high demand period two (M=2.70, SD= 1.08). Conversely, in scenario 2 (low-high-low demand) fatigue ratings appeared to increase across each task demand period (first low task demand period: M=2.71, SD=1.01; first high task demand period: M=3.03, SD=1.42; second low task demand period: M=3.22, SD=1.54) (Fig. 2).

A one way ANOVA was utilized to explore the effect of task demand on fatigue ratings for both scenarios. In scenario 1 (high-low-high demand) Mauchly's test indicated that the assumption of sphericity had been violated, $\chi 2(2) = 9.44$, $p<0.01$. When considering this main effect, therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (E=0.56). No significant differences between fatigue ratings were identified $F(1.12, 7.81) = 2.48$, $p>0.05$. Differences between fatigue ratings in scenario 2 (low-high-low demand) approached significance, $F(2,14) = 3.40$, $p<0.1$. A further review of the descriptive data revealed that averaging across the two fatigue measures per task demand period (one three minutes into the period, and one three minutes before the end of the period) may be masking the effect of task demand on fatigue. Participants' fatigue rating was frequently lower for the first measurement compared to the second measurement of the task demand period. Therefore, ANOVAs were repeated on two fatigue measurements per workload period. In scenario 1 (high-low-high demand) Mauchly's test indicated that the assumption of sphericity had been violated, $\chi 2(14) = 26.82$, $p<0.05$. When considering this main effect, therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (E=0.44). No significant differences between fatigue ratings were identified $F(2.18, 15.22) = 2.82$, $p>0.05$. The ANOVA applied to scenario 2 revealed a main effect of task demand on fatigue ratings $F(5,35) = 2.69$, $p<0.05$. Pairwise comparisons revealed that fatigue ratings were significantly lower at the first fatigue measurement of the first low task demand period (M=2.63, SD=1.06) compared to fatigue ratings in the second low task demand period (first fatigue measurement M=3.13, SD= 1.46, p=0.05; second fatigue measurement M=3.31, SD=1.65), p<0.05). No other differences were significant.

Task demand and performance

Table 2. Mean and standard deviation for arrival aircraft delay (in seconds) in both scenario 1 and scenario 2, averaged across 20 minute task demand periods.

Arrival aircraft delay (secs)	Task demand period 1 (0-20 minutes)		Task demand period 2 (31-50 minutes)		Task demand period 3 (61-80 minutes)	
	M	SD	M	SD	M	SD
Scenario 1 Aircraft delay (High-low-high)	13.88	5.32	7.70	3.6	-1.71	6.92
Scenario 2 Aircraft delay (Low-high-low)	10.48	3.07	9.93	2.54	7.50	4.86

A review of the average delay across 20 minute task demand periods in scenario 1 (high-low-high demand) (Table 2) suggests that participants reduced average aircraft delay across the task demand periods until aircraft were arriving early in the final task demand period (Table 2). The same pattern was seen in scenario 2 (low-high-low demand), although smaller reductions in delay are observed (Table 2). However, in both scenarios, performance variability appears to increase in the final task demand period, indicated by comparatively large standard deviations (Table 2). Data in scenario 1 (high-low-high demand) were further examined with a repeated measures ANOVA. A significant main effect of task demand period was found on arrival delay $F(2,14) = 12.84$, $p<0.005$. Pairwise comparisons revealed that aircraft delay was significantly longer in the first high demand period than the first low demand period ($p<0.05$) and the second high demand ($p<0.01$). Delay was also significantly longer in the first low demand period than the second high demand period ($p<0.05$). Data in scenario 2 (low-high-low demand) were also further examined with a repeated measures ANOVA. No significant differences in arrival aircraft delay were identified $F(2,14) = 3.04$, $p>0.05$.

Discussion

A within-measures design was used to investigate task demand variation on workload, fatigue, and performance. The direction of the task demand transition was manipulated to create two scenarios: scenario 1 - high-low-high demand; scenario 2 - low-high-low demand. Results showed that task demand varied as intended. Descriptive statistics confirmed that equivalent demand periods, regardless of scenario or position, were composed very similarly in terms of controlled aircraft count and arrival aircraft count. This suggests that changes in the covariates or dependent variable are unlikely to be attributed to demand differences between the created scenarios.

As expected, a change in task demand appears to affect both workload and fatigue ratings. Significantly different workload and fatigue ratings were reported within scenario, across task demand periods. However, a key finding of interest is that perception of workload and fatigue appear to differ depending on the demand period preceding the current ratings, in line with previous findings [5]. This finding is observed in the average workload ratings for each task demand period within scenarios (Table 1). In the first scenario (high-low-high task demand), workload is not perceived significantly differently between the first and second high task demand periods. Workload is rated as significantly lower during the low demand period compared to the high demand periods, however. Comparatively, in scenario 2 (low-high-low demand) workload is perceived to be significantly greater in the second low demand period than the first, potentially suggesting that workload is perceived to be greater after the high demand period. This increased workload would not be the result of working to resolve delays from the previous period, as any remaining delays were absorbed in the 10 minute transition period between the stable demand periods. In addition, it is interesting to note that workload was perceived to be higher in the high demand period of scenario 2 than either of the high task demand periods in scenario 1, suggesting that the preceding low demand may have impacted the perception of workload of the high demand period in scenario 2.

These findings indicate that the workload appears to be perceived differently depending on what precedes the time of rating. More specifically, results suggest that in this ATC task, a demand transition pattern of low-high-low demand may result in operators perceiving subsequent high and low demand periods after the initial low demand period as generating a greater workload than equivalent demand periods in a high-low-high demand transition pattern. A similar pattern of findings was seen in participants' fatigue ratings. In scenario 1 (high-low-high demand), fatigue ratings were not significantly different between demand phases. Fatigue ratings did increase in the final high demand period, although not significantly. In contrast, in scenario 2, participants reported on average that fatigued increase with each subsequent task demand period.

Although there is a lack of common agreement regarding the mechanisms by which task demand transitions may impact covariate factors [15], this collection of workload and fatigue findings may be interpreted in the context of Limited Resource theory [16] and arousal theories. Potentially, in scenario 1, the low demand period may have enabled controllers to use this time to recover resources and prepare for the next high task demand period. [17] has previously documented that this is an active control strategy that controllers use during low demand periods, when it is considered safe to do so. This recovery period may then limit the increase of perceived fatigue in the final high task demand period. Arousal theories may provide some insight into why this effect may not be seen in the low-high-low demand transition pattern. Arousal theories suggest that low workload (or underload) may lead to lower arousal, which may limit attentional resources and create boredom and lack of motivation. If a human operator started a task from this point, it may be that the following demand periods are perceived to be more demanding or fatiguing. By the final low demand period, the operator may find it difficult to pay attention. Attentional resources theories suggest however that if preceded by a higher demand, lower demand periods can be utilized to replenish attentional resources, not necessarily reducing arousal to a level that would create negative effects. The application of these theories therefore potentially account for the disparate findings between the different task demand transition patterns.

Performance did not appear to be negatively affected in relation to task demand variation, with delay times reducing across task demand periods within each scenario. Performance variability did increase however across task demand period, as inferred from increasing standard deviations. This pattern of findings for performance measures has also been documented previously, although for vigilance-based performance [7]. The finding of improved aircraft arrival time may be the result of controllers applying strategies to support performance across the demand periods [18].

Although controller strategies were not a direct focus of this research, this finding highlights an important issue for future research considerations. Although this measure of performance indicates that performance in terms of aircraft arrival time was maintained, and even improved, in scenario 2, controllers also reported greater perception of workload and fatigue. It is therefore possible that controllers may have experienced having to work harder to maintain performance, even though this was not observable in the performance measure itself. This result emphasizes that in order to detect, and prevent, performance declines, further research should focus on measures that are sensitive to the operators' experience, and that can be monitored and utilized to detect potential performance decline prior to a performance related incident.

It is acknowledged that these results are provisional, and results need to be interpreted within context. For example, in an air traffic environment, it is easier for the controller to build a picture of the traffic by ramping up with the traffic rather than just starting a session in a high demand period [17]. However, findings do have important implications for the prediction of controller performance in an operational environment. Findings suggest that high and low demand periods can affect controller perception of covariate factors such as workload and fatigue differentially depending on what has happened prior to the current situation. Thus, supervisors may need to pay close attention to the number and direction of transitions that a controller experiences per session to most effectively support controller performance.

Future research should further explore the relationship between previous task demands and the relationship on present controller experience, including the exploration of sudden, and unexpected, transitions. Better predictions are needed to identify and prevent potential performance declines and associated performance-related incidents. Such predictions may be particularly relevant for adaptive automation technologies that support operator performance.

Conclusion

The effect of task demand transitions on covariate factors of workload and fatigue and one efficiency related performance measure was investigated within the context of an air traffic control task. Initial findings suggest that task demand variations affected participants' perceptions of workload and fatigue, although the effect appeared to be influenced by the direction of the previous demand periods. Performance appeared to be maintained across the control session. Previous research has infrequently considered transitions of task demand in an applied environment. Findings are consistent with the description of workload history effects [5], and that equivalent task demand periods can elicit different experiences for a human operator depending on what precedes the time of rating. Attentional resource and arousal theories appear to support interpretation of the results. Further research is required to enhance understanding of demand transition and history effects. Practical applications include guidance for operations room supervisors, and implications for predictions of performance in high and low demand periods, with important implications for identifying and preventing potential performance declines and associated performance-related incidents.

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