The Impact of Handling Qualities on Psychomotor Performance and Operational Stress in a Compensatory Tracking Task

Kyle F. Pietro*, Hyuk Oh, Alex A. Shaver, Rodolphe J. Gentili, Roberto Celi, Bradley D. Hatfield

University of Maryland, College Park
College Park, MD

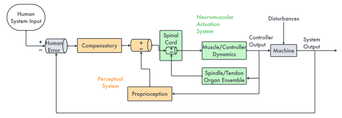
ABSTRACT

Background: Balancing the simplicity and complexity of manual operations is one of the biggest challenges in the design of control systems as these not only influence the performance and safety of human-operators, but also facilitate the reliability and effectiveness of a system. However, the impact of system controllability (e.g., handling qualities (HQ)) on objective measures of the operator's psychomotor performance in conjunction with the corresponding subjective ratings has not been well studied. Thus, this study aims to understand psychomotor performance through the combined assessment of objective biomarkers and subjective ratings during varying levels of task demand and controllability. **Methods:** Fourteen midshipmen in the NROTC completed a series of tasks manipulated by two rotational degrees of freedom (Single-axis, Multi-axis) and three HQ levels (Satisfactory, Unsatisfactory, Unacceptable). Task-related cortical activity (via electroencephalography (EEG)), control performance (via inceptors), and subjective ratings (Bedford Workload Scale (BWS) and NASA Task Load Index (TLX)) were collected for each task. As an objective index of workload, the averaged EEG theta-alpha ratio (TAR) and control performance were computed. Subjective ratings and objective measurements were tested using a two-way repeated measures ANOVA. **Results:** Both BWS and TLX were lower for the Satisfactory-HQ, compared to the Unacceptable-HQ, for both the Single-axis and Multi-axis tasks. Workload indexed by TAR increased within the Single-axis and Multi-axis tasks, but failed to reach statistical significance. **Conclusions:** Our results demonstrated that Unacceptable-HQ is an indicator of operational stress as related to operators' mental health. This implies that properly designed control systems are critical in promoting psychological resilience among service members and civilians and furthermore for their safety and readiness.

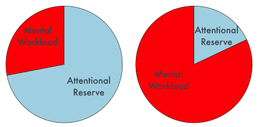
BACKGROUND

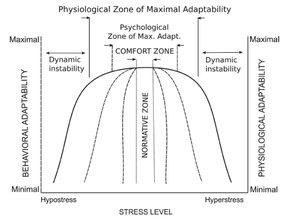
Stress, mental workload, fatigue, distraction, and situational unawareness can cause human errors which may produce inefficiencies to unfortunate disasters [7, 14]. The level of stress and workload perceived by a performer can greatly impact their desired performance. The ability for tactical athletes, medical practitioners, and military personnel amongst all individuals to effectively regulate emotion under mental stress can often be the difference between success and failure. Traditionally, perceived stress, workload, and ratings of handling qualities (HQ) have been assessed through subjective means. Consequently, few studies have examined the stress, workload, and associated HQ ratings through objective means.

- Stress is a dynamic phenomenon associated with active, effortful attempts at adaptation [3]
- One's emotional state is comprised of many factors, including stress and mental workload
- Emotion regulation under stress and adaptation occurs via exposure to optimal stress levels, represented by an inverted-U
- The human information processing system at any moment possesses a finite 'pool' of processing faculties, which has generally become referred to as 'resources' [5, 11, 12]
- The resources required for successful execution of a task is impacted by the perceived stress of the operator, and their appraisal as 'challenge' or 'threat' [16]
- Increased stress has the ability to consume attentional resources resulting in overactivity and disruption such that the operator has issue maintaining concentration, more energy is mobilized than is required, and muscular activation becomes inefficient, even though it is not instrumental to the task [2]
- Psychomotor behavior is broken into two separate branches: mental workload and attentional reserve, where mental workload represents the amount of mental and physical effort required to complete a task, and attentional reserve is simply "what is left over" [10]
- The reduction and/or regulation of operator stress has great applicability such as while driving a vehicle or in the piloting, design, and evaluation of aircraft
- Maximal efficiency of human-operator behavior is desirable as it contributes to safer and more reliable operation of systems
- Human-operator compensation can be interpreted as a decrease in efficiency
- No single measure provides a universal solution in examining operator stress or workload [1]



Theoretical model [8, 6]

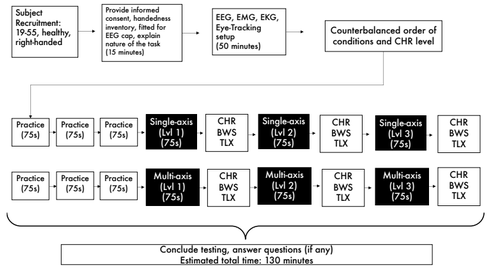


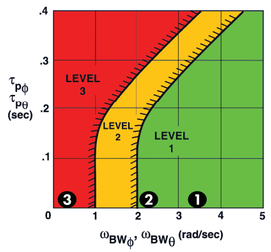


Theoretical model [3]

METHODS

In order to manipulate challenge, (i.e., level of HQ), this experiment adjusted the forcing function bandwidth of the operator's input via a joystick control. The SoS command signal remained constant across all trials, however it is likely that the operator perceived varying levels of stress/workload (i.e., HQ) due to the level of responsiveness of the system. For all figures, HQ levels for Satisfactory, Unsatisfactory, and Unacceptable are represented as HQR 1, 2, 3, respectively.



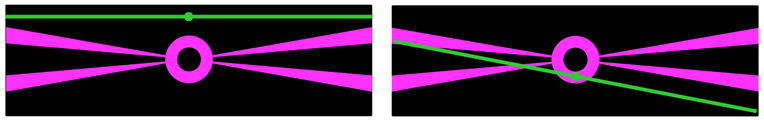


METHODS

The task employed in this experiment is a highly idealized version of pitch and roll control of an aircraft in a turbulent atmosphere, and is based on the display shown below, which consists of a green line representative of the horizon, and a magenta shape (the "bowtie") representative of the aircraft, e.g., the aircraft dashboard. Although the experiment employs an idealized version of an aircraft piloting task, no specific piloting training was required. Participants were asked to aggressively track the displayed green line representing the command signal, and to keep errors within the specified tolerances in Table 1.

Table 1. Performance Standards

		Desired	Adequate
Pitch:	At least x% of the scoring time within pitch attitude error tolerance:	50% $\pm 1°$	75% $\pm 2°$
Roll:	At least x% of the scoring time within roll attitude error tolerance:	50% $\pm 5°$	75% $\pm 10°$



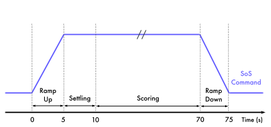
(a) (b)

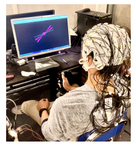
Bowtie heads-up display (magenta polygon) which participants controlled during the compensatory tracking tasks
(a) Single-axis Condition, **(b)** Multi-axis Condition [9]

Ss Characteristics (N=14)

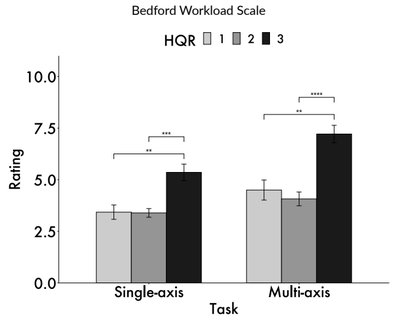
Variable	Overall
Age (years)	20.6 (0.4)
Gender	
F	3
M	11
Simulation (Hours)	1.6 (0.5)
Video Game (Hours)	6.2 (2.0)

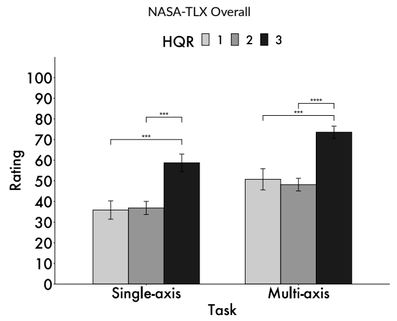
Mean (S.E.M.)

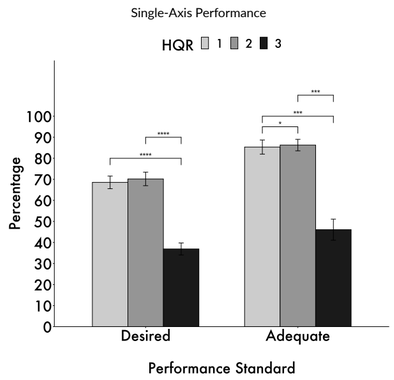


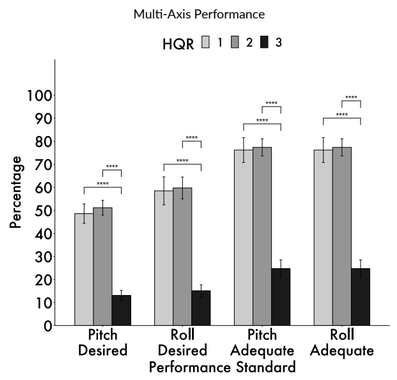


RESULTS



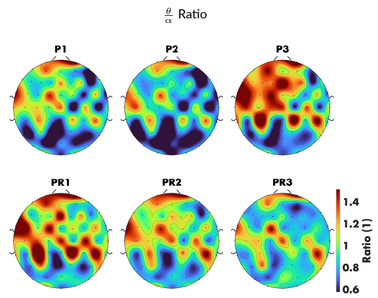


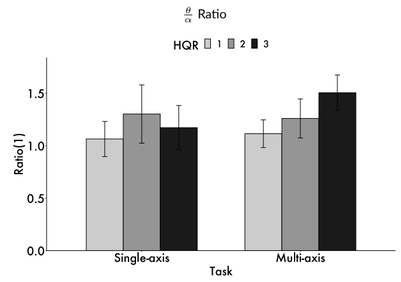




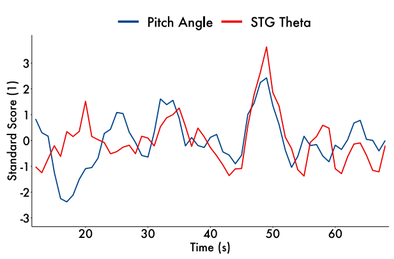
RESULTS

Psychophysiological Measures	Bandwidth (Hz)	Index of Increased Mental Workload
EEG - Alpha (α)	8-13	Decrease
EEG - Theta (θ)	4-8	Increase
EEG - TAR ($\frac{\theta}{\alpha}$ Ratio)	-	Increase

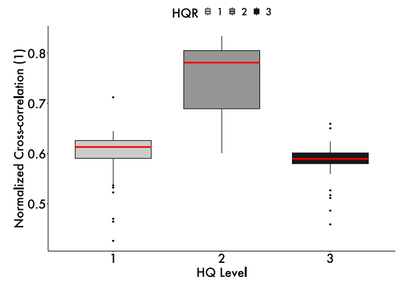




Single-axis Performance-Superior Temporal Gyrus Theta Activity (Single Subject)



Single-axis Brain-Behavior Correlation



CONCLUSIONS

- BWS ratings significantly increased from the Satisfactory-HQ compared to the Unacceptable-HQ for Single- and Multi-axis tasks
- NASA-TLX ratings significantly increased from the Satisfactory-HQ compared to the Unacceptable-HQ for Single- and Multi-axis tasks
- Workload indexed by TAR increased from the Satisfactory-HQ compared to the Unacceptable-HQ for Single- and Multi-axis tasks
- Task performance greatly decreased as challenge increased for both the Single- and Multi-axis tasks
- Usage of brain-behavior correlation can highlight temporally synchronous nature between perception and action
- Increases in perceived stress via lower HQ can impact the synchronous coordination between brain and behavior
- Workload related stress may follow an inverted-U type paradigm, which signifies a possible 'optimal' level of workload associated with HQ levels for efficient adaptability and performance [3]
- The objective measure of EEG is sensitive to variation in task demand; this finding promises to be useful and effective in engineering human-machine interfaces to preserve neural efficiency of operator performance and maximize psychological resilience, safety, and readiness among service members and civilians
- Suboptimal design of human-machine interfaces may result in increased perceived stress, workload, and attenuated performance
- High levels of workload could lead to chronic stress and over-activation, resulting in poor health outcomes of human-operators
- Future implications also include improving our understanding of suboptimal aircraft HQ as it relates to the long-term effects of flight-related stress and the development of post-traumatic stress disorder, anxiety disorders, depression, and spinal pain [7]
- Future studies will examine the time-frequency elements of workload to capture the dynamic nature of the brain state with increased temporal resolution, the goal of which will be to reveal neural correlates of handling quality, degree of freedom recruitment, decision-making process, and their associations with mental workload

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REFERENCES

*kpietro@umd.edu