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Human Optimization and Performance Enhancement in Flight via Real-time Biofeedback (Project HAVE HOPE)

Michael S. Fritts

HUMAN OPTIMIZATION AND PERFORMANCE ENHANCEMENT IN FLIGHT VIA REAL-TIME BIOFEEDBACK (PROJECT HAVE HOPE)

THESIS

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DEPARTMENT OF THE AIR FORCE
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(PROJECT HAVE HOPE)

THESIS

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Abstract

Human operators of aviation systems are not fully aware and cognizant of the myriad of factors that affect their performance on a daily basis. Human-machine systems need an avenue to monitor operators, display physiological metrics, and provide alerts that augment the user in an intuitive and operationally relevant manner. Operator physiological and cognitive (PC) state embodies current short term and long-term influences on the capabilities and limitations of an operator. Operator enhancement informs individuals of PC state and has the potential to increase overall situation awareness (SA). This research aimed specifically at enhancing operator awareness, decision-making, and performance in flight via real-time biofeedback.

A four-phase, chronological, and build-up approach was implemented that commenced with basic hardware testing in a centrifuge and culminated in F-16 flights with operators augmented by real-time biofeedback displays. A prototype Portable Electrocardiogram Unit (PECGU) was designed and proven to accurately measure heart rate (HR), and display HR metrics real-time, percentage heart rate reserve (%HRR).

Results showed that %HRR was not a good sole predictor of cognitive state. Cognitive responses indicated some correlation with %HRR, but were influenced by environment (centrifuge vs. flight). Subjective perceived exertion levels in subjects did not show statistically significant changes during test with biofeedback. A G-tracking task was evaluated during centrifuge and flight tests. One of four subjects showed statistically significant improvement during the centrifuge task. One of three subjects statistically improved during airborne G-tracking. Analysis of the human systems integration (HSI) of a %HRR biofeedback display in fighter aircraft cockpits generated key design features and recommendations for future military utility.

This research marked the first time pilot HR was accurately measured and processed in flight, yielding a real-time biofeedback display. Overall, results could not be characterized by a single HR metric. A wide range of biosensors is needed to define operator PC state. There is hope in the future for an individualized, all-inclusive, and data-driven complex biofeedback algorithm, which ultimately presents a streamlined and intuitive PC state index. The potential to change how human system health monitoring is implemented and displayed may have tremendous enduring benefits to the warfighter.

To My Family

The support provided to me by my wife made working until midnight, sound much worse than it actually was. Also, to my daughter and my son, whose smiling faces provided encouragement and prospective when the time was needed.

Acknowledgments

This research spanned nearly 30 months, three states, two temporary duty (TDY) trips, and assignments at both the Air Force Institute of Technology (AFIT) and the United States Air Force Test Pilot School (USAFTPS). There is a long list of key individuals who were critical to my successful completion of this project. I am humbled by the opportunity to have worked with such talented people and my greatest fear is forgetting someone.

I would like to thank my faculty advisor, Dr. Chad Hale (USAF, ret.) for his mentorship over the past two years and agreeing to take on such a non-traditional thesis project outside conventional lanes at AFIT. The autonomy and flexibility provided to me allowed for growth and self-reliance while learning the art of scholarly research.

This project would absolutely not have been possible without the dedication from my team at the 711th Human Performance Wing (711 HPW) at Wright-Patterson AFB, OH. Among the team, I would like to thank my sponsor, Dr. Ryan Mayes for both the support and latitude provided to me in this endeavor. I would like to express my sincere appreciation to Dr. David Burch and Megan Gallo who stayed on for the ride for two years of bi-weekly meetings and telecoms. Their insight and sweat made this project possible. Furthermore, Warren Carroll's work aiding in project management provided a key beacon of continuity for nearly two years. Dan Pohlman's working leading up to our first centrifuge trip and the follow on data analysis he, Dr. Converse Griffin, and Joseph Wagner accomplished was extremely beneficial. Dr. Jim McEachen provided great insights into the intricacies of flight test during very early discussion stages. Charles Harding's work on finalizing hardware was critical prior to centrifuge and flight tests.

To the members of my Test Management Project (TMP) team at USAFTPS, not all of you volunteered for this project when you heard it entailed a trip up to 9 Gs in the centrifuge, but you all now proudly wear the HAVE HOPE patch! Captain Philip Downing, Flt Lt Adam Francki, Captain Weston Hanoka, and Captain Mark Shaker, thank you for your dedication as a team member on this venture. Your ideas, expertise, and sweat are greatly appreciated and made successful completion of this project possible.

USAFTPS played an essential role in shaping this project. As colleagues of the Test Management Branch, Lillian Aguilar, Dan Carroll, and Lt Col Joseph McGill offered continuous support. Senior Test Pilots Tom Hill and Bill Gray provided insights into test conduct prior to my arrival at TPS. Division Chief of Curriculum Standards Major Dan Montes's insights both on TPS staff and on my thesis committee are also greatly appreciated.

Cliff Hebbeler was a solid source of continuity and whose insight and expertise was essential to incorporating our hardware into the cockpit. Additional key team members at Edwards AFB, CA included Captain Anne Lee, Captain Tom Gedulig, TSgt and Natasha Titemore.

Members of the KBRWyle, Science, Technology, and Engineering Group enabled our phase-based build-up approach to testing by going out of their way to accommodate our unique testing requests during two separate trips. Their support was appreciated and essential to successful project completion.

-Michael S. Fritts

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List of Abbreviations

%HRR	Percent Heart Rate Reserve
%TOT	Percentage Time on Target
711 HPW	711th Human Performance Wing
AC	Aircraft Commander
ACM	Air Combat Maneuvering
AFB	Air Force Base
AFE	Aircrew Flight Equipment
AFIT	Air Force Institute of Technology
AFMS	Air Force Medical Service
AFRL	Air Force Research Lab
AFTCI	Air Force Test Center Instruction
AGCAS	Automated Ground Collision Avoidance System
AGSM	Anti-G Straining Maneuver
AHP	Analytic Hierarchy Process
AMPSS	Aircrew Mounted Physiologic Sensor Suite
ANOVA	Analysis of Variance
ATAGS	Advanced Technology Anti-G Suit
ATP	Adenosine Triphosphate
BCB	Brooks City-Base
BFM	Basic Fighter Maneuvers
BPM	Beats Per Minute
BVR	Beyond Visual Range
BWS	Bedford Workload Scale
C1	Initial Hardware and Subject Centrifuge Trials
C2	Training and Build-Up Approach Centrifuge Testing
CAS	Close Air Support
CATS	Cognitive Assessment Toolkit System
CBA	Capabilities Based Assessment
CCF	Cross-Correlation Function
CO_2	Carbon Dioxide
COS	Cerebral Oxygen Status
CPD	Composite Parameter Display
CPH	Cognitive Pilot Helmet
DAS	Data Acquisition System
ECG	Electrocardiogram
EEG	Electroencephalogram
Elbit	Elbit Systems Canary Pilot Health Monitoring System
EMI	Electromagnetic Interference
EMIC	Electromagnetic Interference Compatibility
F1	Flight Testing
FCP	Front Cockpit
FF	Fuel Flow
FOV	Field of View

FTT	Flight Test Technique
G	Gravitational Forces
Garmin	Garmin Fenix 3 Sapphire HR Monitor Watch
G-LOC	G-induced loss of consciousness
G-suits	Gravitational Suits
GTMRP	Greater-Than-Minimal Risk Protocol
GUI	Graphical User Interface
HF	High-Frequency Spectral Power
HGAHSP	High-G Acceleration Human Subject Panel
HOPE	Human Optimization and Performance Enhancement
HOTAS	Hands-on-Throttle-and-Stick
HR	Heart Rate
HR_{max}	Maximum Heart Rate
HR_{rest}	Resting Heart Rate
HRV	Heart Rate Variability
HSI	Human Systems Integration
HUD	Heads-Up-Display
HUT	Hardware Under Test
IMS	Inductive Monitoring System
IRB	Institutional Review Board
JASDF	Japanese Air Self-Defense Force
KBRWyle	KBRWyle Science, Technology, and Engineering Group
L1	Laboratory VO_{2max} Testing
LF	Low-Frequency Spectral Power
LSS	Life Support System
MDLS	Miniature Dynamic Light Scattering
MDOC	Mission-Driven Operator-Compensated
MDS	Mission-Design Series
MIL-STD	Military Standard
MOP	Measure of Performance
NAMRU-D	Naval Medical Research Unit Dayton
NASA	National Aeronautics and Space Administration
NCCF	Normalized Cross-Correlation Function
Ng	Gas Generator Speed
NHSR	Not-Human Subject Research
NIRS	Near-Infrared Spectroscopy
Np	Power Turbine Speed
NRR	Negligible Risk Review
O_2	Oxygen
OPL	Operator Performance Laboratory
Ops Check	Operational Procedure Assessment
P2CP	Pilot Physiologic and Cognitive Performance
PBG	Pressure Breathing under G
PC	Physiologic and Cognitive
PECGU	Portable Electrocardiogram Unit
PMU	Portable Metabolic Unit

PVI	Pilot Vehicle Interface
RASCAL	Rotorcraft Aircrew Systems Concepts Airborne Laboratory
RER	Respiratory Exchange Ratio
RMS	Root Mean Square
RPE	Rating of Perceived Exertion
RTB	Return to Base
SA	Situation Awareness
SACM	Simulated Air Combat Maneuvering
SPO	System Program Office
SRB	Safety Review Board
STO	Specific Test Objective
SUT	System Under Test
SWORD	Subjective Workload Dominance
T&E	Test and Evaluation
TC	Test Conductor
TD	Test Director
TLX	Task Load Index
TMP	Test Management Project
TP	Test Pilot
TPS	Test Pilot School
Tq	Engine Torque
UAS	Unmanned Aerial Systems
UPG	Upper Pressure Garment
USAF	United States Air Force
USAFSAM	United States Air Force School of Aerospace Medicine
USAFTPS	United States Air Force Test Pilot School
UTD	Unit Training Device
VMC	Visual Meteorological Conditions
VO_2	Oxygen Consumption Rate
VO_{2max}	Maximal Oxygen Consumption Rate
WVR	Within Visual Range
Zephyr	Zephyr BioHarness 3.0

Forward

January 2, 2014

It happened during the 4th engagement of a routine high aspect basic fighter maneuvers (BFM) training mission while I was deployed to Southwest Asia. I was piloting an F-22 Raptor while attempting to maneuver to a position of advantage against an F-15. Outside of the normal physiological stressors of elevated heart rate, breathing rate, perspiration, fatigue, and dehydration I was accustomed to, I felt completely normal prior to calling, "turn in, fights on!" In driving specific training objectives, I elected to force a "single circle" fight after a left-to-left pass at the second merge, an accepted and safe tactical decision. This maneuver required an aggressive left-to-right roll about the aircraft longitudinal. Additionally, I remember aggressively rotating my head from looking out the left side of the cockpit to the right side in an attempt to immediately reacquire sight of the F-15. I had performed this maneuver hundreds of times in the past, yet for some reason on that day the coupled effect of aircraft roll and rapid head transition generated an alternate output for my vestibular system, or inner ear. While my actual aircraft state after the maneuver resembled a slightly nose low, 90 degree right banked turn, my perceived visual and physiological cues were telling me I was in a continuous and rapid right roll about the aircraft longitudinal axis while nose low toward the desert floor. Initially I thought my F-22 had experienced some type of catastrophic aileron or rudder failure, but I later realized I was spatially disoriented and fighting my vestibular perceptions to safely fly the airplane.

The Coriolis Illusion, a type of spatial disorientation phenomenon, involves simultaneous stimulation of two semicircular canals coupled with sudden tilting of a pilot's head while the aircraft is turning. The net result is an almost unbearable sensation that the aircraft is rolling, pitching, or yawing, (comparable to a sensation of tumbling down a hillside) which can rapidly lead to pilot disorientation and loss of aircraft control (Antunano, 2016).

I couldn't read my heads-up-display (HUD), but based on my last crosscheck I knew I had about 15 seconds to react before my aircraft reached the 6,000ft uncontrolled ejection altitude we brief before every flight. For those next 15 seconds, I remember thinking about where the ejection handle was located and wondered if this was going to be the day I either died, ejected, or both. I thought if I can just pull back on the control stick enough to turn brown desert floor into clear blue sky, I might buy myself some time. I did just that, recovered the aircraft from the nose low dive, and within 60 seconds my vestibular system had stabilized enough that I could cautiously fly the F-22 back to base.

I got lucky that day. But what if there were pre-indications that my physiological and cognitive (PC) state was limited or impaired in some way? What if biosensors could have monitored my PC state and provided objective real-time biofeedback prior to the tactical engagement? Would my tactical decisions have changed?

-Michael "Hijack" Fritts

HUMAN OPTIMIZATION AND PERFORMANCE ENHANCEMENT IN FLIGHT VIA REAL-TIME BIOFEEDBACK

1. Introduction

1.1 Background and Motivation

From the moment the Wright Brothers took flight on December 17, 1903 in the first heavier-than-air human flight, mankind has pushed the limits of human performance in aviation. Aircraft began flying faster, higher, and radially accelerating, growing a need to design cockpits, oxygen masks, and gravitational suits (G-suits) all with a common goal of keeping the pilot alive. Today the performance and processing capabilities of aircraft surpass the physiological and cognitive limits of their human operators. The first one hundred years of human flight aimed at maximizing the performance of the airplane, while simply keeping operators alive. Little focus has been put on optimizing the human and maximizing their performance, too. This research strives to expand the human performance envelope in an effort to enhance capabilities of the human-machine system in an aerospace environment.

A large demand is placed on humans to execute soundly in high performance aircraft. Split-second missioned decisions, sensor/ display information overload, and physical stressors (gravitational, thermal, and respiratory) that plague the body are all challenges faced by fighter pilots during a routine mission. With the rise of artificial intelligence technology and machine learning algorithms being applied to unmanned aerial systems (UASs), is the window of opportunity for manned flight really closing? Why should additional research be placed on humans and their inherent limitations in the cockpit? The simple acknowledgement of these technological advances only further emphasizes the need for better understanding of human-machine systems. Future warfare will be waged with human-machine teams consisting of mixed manned-unmanned airborne formations and ground assault vehicles. Such configurations will leverage human strengths paired with computational merits. Yet, human error remains a large contributor to aviation mishaps. Human-machine systems need an avenue to monitor operators, display physiological metrics, and provide alerts that augment the use in an intuitive and operationally relevant manner.

1.2 Research Problem, Key Terms, and Justification

Human operators of aviation systems are not fully aware and cognizant of the myriad of factors that affect their performance on a daily basis. Why do humans perform better on some days than they do on others? An operational need exists for a deeper understanding of the operator physiological and cognitive (PC) state and how performance is affected by fluctuating mission tasks, which drive changes to the operator environment.

Operator PC state embodies the current short term and long term influences on the capabilities and limitations of an operator. Environmental inputs capture the changing conditions the operator undergoes over the course of a mission due to mission tasks. Pilots are compensated with G-suits to help maintain blood flow to the brain during sustained gravitational forces (Gs) above 6 Gs. Upper pressure garments (UPG) provide added protection in the event of rapid cockpit decompression during high altitude flight. Positive pressure breathing under Gs (PBG) deliver pilots increased forced air pressure through their oxygen masks to contest respiratory challenges and “air hunger” under high Gs. Lastly, flight suits and gloves provide thermal protection while helmet visors shield eyes from ambient light extremes. Seen in Figure 1 below, all of these aircrew flight equipment (AFE) articles help pilots combat the physiological challenges encountered due to dynamic environmental inputs. Finally, performance is the output of environmental inputs, compensation, and operator PC state. Therefore, performance is directly affected by the demands of mission tasks.

Figure 1: Aircrew Flight Equipment

Operator enhancement projects what a human is capable of achieving when fully informed of their PC state. This augmentation has the potential to increase overall situation awareness (SA) through the use of biofeedback. Biofeedback is a mind-body aid that uses electronic sensors to measure physiological processes and help individuals gain a better understanding and control over normally automatic bodily functions (Gilbert & Moss, 2002). The idea of biofeedback in aviation systems has been introduced (Calhoun, 2000), but little research has been done to support implementation.

In 2014, the Air Force Medical Service (AFMS) highlighted a capabilities based assessment (CBA) gap that identified the strategic need for a Pilot Physiology and Cognitive Performance (P2CP) indicator:

> *The AF needs to quickly and accurately identify and prevent pilot/operator incapacitation from any/all causes. The long-term goal is in-flight monitoring that would focus on physiologic and performance measures that are susceptible to stressors such as sleep loss, extended duty day, and the specific physiologic conditions faced by pilots in cockpit/ground station environments. Need an objective, real-time mechanism to assess and monitor the performance (cognition, reaction time, fatigue, impact of medications or illness) of console operators (space, cyber, missile, RPA) (AFMS CBA-2014).*

The P2CP program's desired end state aims to incorporate biofeedback into aviation systems by providing both cockpit and ground station operators with an integrated suite of sensors, analytics, and real-time data visualization capability. This capability will objectively evaluate and feedback an aviator's cognitive and physiologic performance in an operationally relevant manner.

1.3 Research Question

While the necessity for operator state enhancement is prevalent and needs to be addressed across the full spectrum of human-machine systems in the aviation community, this research is aimed specifically at enhancing pilots SA of their PC state in high performance aircraft. As such, this research addresses the following question:

How can a real-time biofeedback visualization of operator physiological and cognitive state enhance awareness, decision-making, and performance?

1.4 Research Objectives and Scope

This research aims to gain a better understanding of the benefits and implications of providing a pilot with real-time biofeedback, which informs the operator how their body is performing both physiologically and cognitively under the demanding environment of high performance aircraft. Recent studies have assessed biometrics and biofeedback while evaluating their applications to sports medicine and human performance. Paul and Garg (2012) explored the advantages of biofeedback to control anxiety and increase performance among a sample of university basketball players. Further, studies of elite cyclists support a strong correlation between maximal oxygen consumption (VO_{2max}) rate and heart rate (HR) intensity (Lounana, Campion, Noakes, & Medelli, 2007). Additionally, flight studies using a mobile electrocardiogram (ECG) HR recorder show heart rate variability (HRV) increases during times of higher psychophysiological workload while airborne compared to pre-flight and post-flight conditions (Skibniewski et al., 2015). To date the most relevant studies attempting to synthesize the challenges of PC state and workload in flight through the use of biosensors were done using a Cognitive Assessment Toolkit System (CATS) developed by the Operator Performance Laboratory (OPL) at the University of Iowa (Engler, Schnell, & Walwanis, 2013). The OPL applied their CATS technology in simulated real-world fighter aircraft combat scenarios, striving to create the ultimate Cognitive Pilot Helmet (CPH) that could serve as a "gateway to human information" (Schnell, Melzer, & Robbins, 2009). Evidence suggests that while attempts to capture elements of individual PC state have been done, no studies have investigated the effects of biofeedback on operator ability to assess their own PC state.

This research only measured and displayed HR data to aid in operator PC state recognition. Future P2CP efforts should incorporate the full spectrum of human biosensor technology discussed in Chapter 2. The research question is supported by a methodology and experimental design broken down into four primary phases. Each phase is supported by specific test objectives (STOs) and measures of performance (MOPs) as highlighted in Table 1 below.

Table 1: Specific Test Objectives (STOs) and Measures of Performance (MOPs)

Phase 1 (C1)	**Initial hardware and subject centrifuge trials**
	STO 1: Assess initial hardware and test profile
	MOP 1: Cardiorespiratory response
	MOP 2: Tracking performance
	MOP 3: Workload Level
	MOP 4: Hardware accuracy
Phase 2 (L1)	**Laboratory VO_{2max} testing**
	STO 2: Determine operator peak physiologic output
	MOP 1: Maximal Oxygen Consumption (VO_{2max})
Phase 3 (C2)	**Training and build-up approach centrifuge testing**
Phase 4 (F1)	**Flight testing**
	*Combined STOs and MOPs for phases 3 and 4
	STO 3: Determine operator PC state
	MOP 1: Percentage Heart Rate Reserve (%HRR)
	MOP 2: Portable ECG Unit (PECGU) Accuracy
	MOP 3: Cognitive State
	STO 4: Determine the effect of providing biofeedback on operator PC state awareness
	MOP 1: Awareness of PC state without %HRR biofeedback
	MOP 2: Awareness of PC state with %HRR biofeedback
	STO 5: Determine effect of providing biofeedbaack on decision-making
	MOP 1: Decision-making without %HRR biofeedback
	MOP 2: Decision-making with %HRR biofeedback
	STO 6: Determine effect of providing biofeedback on tracking performance
	MOP 1: Centrifuge tracking task accuracy without biofeedback
	MOP 2: Centrifuge tracking task accuracy with biofeedback
	MOP 3: Airborne G-tracking accuracy without biofeedback
	MOP 4: Airborne G-tracking accuracy with biofeedback
	STO 7: Evaluate human system integration of biofeedback display into fighter cockpit
	MOP 1: Usability of display
	STO 8: Collect Aircrew Mounted Physiologic Sensor Suite (AMPSS 3.0) Data

1.5 Methodology, Materials, Equipment, and Evaluation Standards

Data collection and analysis was broken up into the four previously mentioned phases in Table 1. Evaluation methods varied based on location and experiment type, but predominantly provided consistency of assessment techniques between phases.

1.5.1 Phase 1 (C1): Initial Hardware and Subject Centrifuge Trials

Phase 1 was supported by the aid of KBRWyle Science, Technology and Engineering Group (KBRWyle) at Brooks City-Base (BCB) in San Antonio, TX from 1 to 4 November 2016. Seven test subjects from the High-G Acceleration Human Subject Panel (HGAHSP) at BCB (referred to as Subjects 1 through 7) were used to evaluate several initial proposed HR collection hardware configurations and assess the planned test profile. During trials subjects were required to participate in tracking tasks that consisted of manipulating a flight control stick while tracking a target in a flight simulator.

HGAHSP subjects are volunteer members that participate in monthly centrifuge testing. Level of experience varies. Centrifuge exposure and G proficiency is greater than the average high performance aircraft operator, but tracking task proficiency is lower than the average operator. HGAHSP subjects were only used in Phase 1 testing and were not part of the United States Air Force Test Pilot School (USAFTPS) 17A HAVE HOPE Test Management Project (TMP) team.

1.5.1.1 Phase 1 (C1): Materials and Equipment

All subjects were outfitted with AFE gear consisting of the following: flight suit, HGU-55/P flight helmet, MBU-20/P oxygen mask, and CSU-23P Advanced Technology Anti-G Suit (ATAGS). Additionally, KBRWyle ECG leads were attached to the test subject chest to provide a "truth source" of HR data. Additional hardware used consisted of the following: Portable Electrocardiogram Unit (PECGU), Aircrew Mounted Physiologic Sensor Suite (AMPSS) 2.5, Zephyr BioHarness 3.0 (Zephyr), and Elbit

Systems Canary Pilot Health Monitoring System (Elbit). A detailed description of hardware used is included in Chapter 3.

1.5.2 Phase 2 (L1): Laboratory VO_{2max} Testing

Phase 2 testing was conducted from 13 to 14 July 2017 at the Physical Therapy clinic at Edwards AFB, CA by trained research team members from the 412th Medical Group. Test administrators were certified to administer a VO_{2max} test. Five test subjects (referred to as Subjects A through E) consisted of members of the USAFTPS 17A HAVE HOPE TMP team. Subjects performed a VO_{2max} test on a treadmill to determine their exercise-base maximum heart rate (HR_{max}).

1.5.2.1 Phase 2 (L1): Materials and Equipment

Five ECG adhesive electrodes were placed along subject chest cavity to measure HR. A standard treadmill was used to conduct the test. Additional hardware used consisted of a Portable Metabolic Unit (PMU) and Garmin Fenix 3 Sapphire HR Monitor Watch (Garmin). A detailed description of hardware used is included in Chapter 3.

1.5.3 Phase 3 (C2): Training and Build-up Approach Centrifuge Testing

Phase 3 testing was conducted from 14 to 16 August 2017 with the support of KBRWyle at BCB. Subjects A through E from the USAFTPS 17A HAVE HOPE TMP team underwent initial centrifuge training and conducted data collection as a build-up approach for future flight test.

1.5.3.1 Phase 3 (C2): Materials and Equipment

Subjects used the same AFE gear, flight simulator, and PECGU as described in Phase 1. Additionally, as described in Phase 2, the Garmin was worn as an additional data source and backup data collection measure in the event PECGU HR data were lost or the hardware became inoperative. Additional hardware used consisted of the following: GETAC T800 tablet with biofeedback display, GETAC thigh holster, and AMPSS 3.0. A detailed description of the hardware introduced in this phase is included in Chapter 3.

1.5.4 Phase 4 (F1): Flight Test

Phase 4 testing was conducted from 5 to 18 September 2017 in the R-2508 complex at Edwards AFB, CA with the aid of USAFTPS staff, technical support, aircraft, and facilities. Subjects A through E from the USAFTPS 17A HAVE HOPE TMP team conducted flight test using Data Acquisition System (DAS) equipped F-16DM aircraft, tail numbers 87-0391 and 90-0797. A total of 13 test sorties for a total of 7.4 hours were flown.

1.5.4.1 Phase 4 (F1): Materials and Equipment

Predominantly, Phase 4 materials and equipment mirrored those used in Phase 3. Subjects used the same AFE gear, PECGU, GETAC T800 biofeedback display, and Garmin as described in previous phases. No new hardware was introduced in this phase, but slight modifications were made to existing hardware. A detailed description of the hardware used is included in Chapter 3.

1.5.5 Testing Approval: Institutional Review Board and Negligible Risk Review

An Institutional Review Board (IRB) is a required anytime testing is performed on or with human subjects. The IRB committee applies research ethics and reviews the proposed testing methods to ensure they are ethical and confirms safe practices for human subjects. Testing conducted using human subjects, but executed where hardware or processes are the primary systems under test (SUT), still requires an IRB but is categorized as Not Human Subject Research (NHSR). Testing in which humans are the primary SUT qualifies under a Greater-Than-Minimal Risk Protocol (GTMRP). Testing for Phase 1, categorized as NHSR, was requested and approved through the IRB of Air Force Research Lab (AFRL). Testing for Phases 2 through 4 highlighted a GTMRP and was approved for the protection of human subjects by the Naval Medical Research Unit Dayton (NAMRU-D) IRB under protocol number NAMRUD.2017.0013.

A Negligible Risk Review (NRR) is a safety process required by Air Force Test Center Instruction 91-202 (AFTCI) Edwards Air Force Base (AFB) Supplement for the conduct of low-risk preliminary testing. A certified NRR ensures internal safety and technical procedures are used to conduct adequate planning, execution, and reporting of testing prior to a Safety Review Board (SRB). Testing for Phases 2 and 3 required an NRR in order to perform hardware compatibility, ground electromagnetic interference (EMI), laboratory VO_{2max}, and centrifuge testing.

1.6 Research Sponsor

The primary sponsor for this research was the USAF School of Aerospace Medicine (USAFSAM), a member of the 711th Human Performance Wing (711 HPW) of AFRL. Additional sponsors include the USAFTPS and Air Force Institute of Technology (AFIT).

1.7 Future Contributions

This research directly contributed to the desired end-state of the P2CP program being tackled by AFMS. Studies of the human response to augmented flight through the use of biofeedback will allow a deeper understanding of the benefits and limitations of future human-machine research in aviation systems. P2CP goals include development of a more robust biosensor suite that will incorporate all aspects of the human PC state. Basic studies of cardio and respiratory responses will help gain momentum for studying biofeedback in flight and lead to future knowledge and investment. This includes, but is not limited to, incorporation of ocular metrics, electroencephalography (EEG), blood flow sensors, hydration sensors, and cerebral oximetry.

Additional contributions include identification of the capabilities and limitations of the AMPSS oxygen mask and all component sensors. Additional pilot feedback is expected into the design and incorporation of a biofeedback device in aircraft cockpits.

1.8 Chapter Summary

This thesis is organized into five chapters. Chapter 1 serves as an introduction to the background and project motivation as well as summary of the remaining chapters. Chapter 2 encompasses a review of literature conducted by the author supported by studies in human performance limitations in aviation, human-machine systems, biofeedback, human physiology, and PC sensors. Chapter 3 contains a detailed description of the research methodology, materials, and equipment. Chapter 4 incorporates results from Phases 1 through 4 and analysis of experimental data collection drawing correlations between laboratory, centrifuge, and flight test. The proposed research question, STOs and MOPs are addressed. Chapter 5 includes final conclusions and recommendations for future research. Further information from all phases can be found in the appendices.

2. Literature Review

2.1 Chapter Introduction

To set the necessary framework for this research, a review of literature spanning multiple fields was necessary. Chapter 2 encapsulates the current state of research, as well as knowledge gaps pertaining to a problem that spans fields of human physiology, biofeedback, human-machine systems, physiological and cognitive (PC) biosensors, workload, and human performance.

The first section of this chapter highlights a myriad of factors that contribute to operator PC state. Additional terms such as operator compensation, environmental inputs, operator performance, and operator enhancement are all defined. The second section details the techniques, capabilities, and limitations of operator physiological measurement in flight. Third, explanations are provided of both subjective and objective measures for characterizing levels of operator workload. The fourth section elaborates on current research and definitions pertaining to heart rate metrics. Lastly, a brief explanation is provided of how exercise intensity affects energy transfer and oxygen transport in the human body.

2.2 Air Force Operator Enhancement Initiatives

The rise of wearable technology ("wearables") and mobile medical devices today allow humans to actively track their current PC state better than ever by gaining a deeper awareness of their capabilities through biofeedback. Mobile computing has shown potential to support safety-critical systems, aircraft control, and medical applications (Motti & Caine, 2014). When looking to optimize human performance in flight, the use of wearable technology and biosensors within the cockpit environment is a natural collaboration.

The necessity for operator state enhancement is prevalent and needs to be addressed across the full spectrum of human-machine systems in the aviation community. In 2014, the Air Force Medical Service (AFMS) highlighted a capabilities based assessment (CBA) gap that identified the strategic need for a Pilot Physiology and Cognitive Performance (P2CP) indicator (AFMS CBA-2014). The P2CP program desired end state aims to incorporate biofeedback into aviation systems by providing console operators with an integrated suite of sensors, analytics, and real-time data visualization capability. This augmentation will objectively evaluate and display aviator PC performance in an operationally relevant manner. The goals of P2CP are directly in line with this research, which aims specifically at optimizing pilots in high performance aircraft via real-time heart rate (HR) biofeedback.

2.3 Operator PC State, Compensation, Performance, and Enhancement

Countless factors contribute to an operator's performance in flight. Performance is defined as the precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task (Hodgkinson, 1999). This performance is calculated as a measured output from the overall human-machine augmented system. To facilitate further discussion, several definitions where established for this research and are highlighted in the following sections of this chapter.

First, operator *PC state,* as shown in the feedback control diagram in Figure 2 is made up of six primary components. Short-term dynamic factors that shape operator PC state include nutrition/hydration, sleep, and currency/training. Nutritional intake before any athletic exercise has been proven to directly affect physiological performance (Rodriguez, DiMarco, & Langley, 2010). Sleep and circadian rhythm are most affected by lifestyle decisions from the previous 24 hours. However, sleep cycle changes proceeding up to seven days prior can also contribute to bodily health. Finally, the 30/60/90-day currency (number/type of sorties flown) and recent training program of a pilot directly affect his/her ability to not only perform a specific mission task correct, but also excel above personal baseline execution.

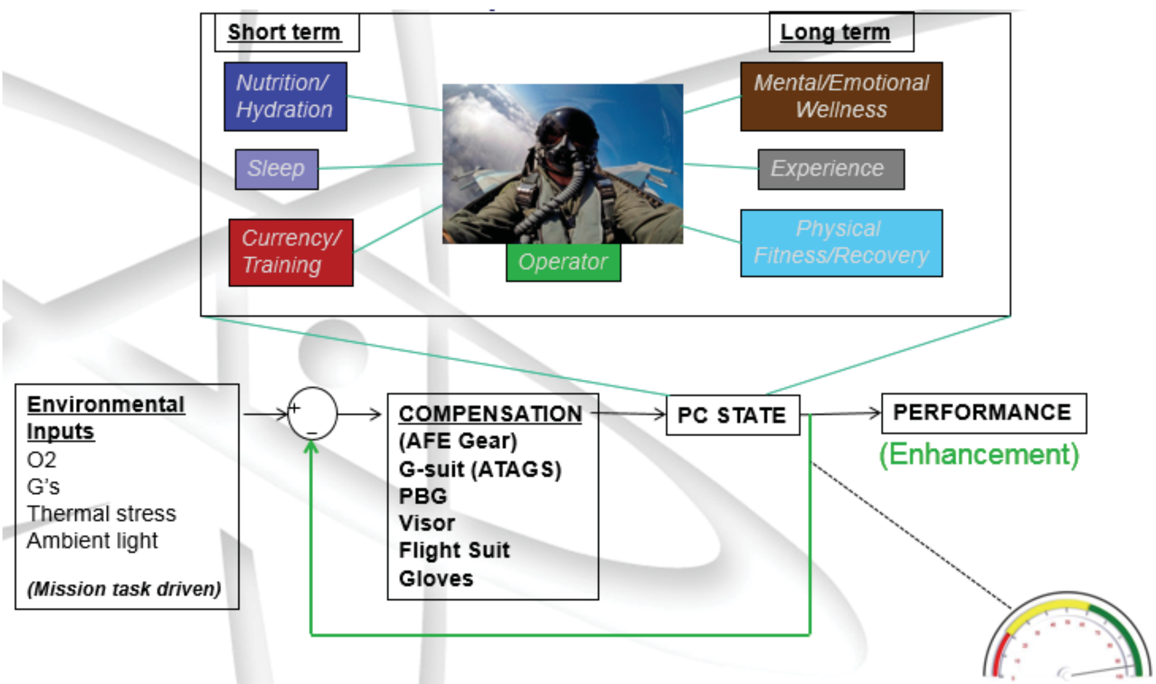

Figure 2: Mission-Driven Operator-Compensated System

Long term dynamic factors that shape operator PC state include pilot mental/emotional wellness, career flying experience, as well as physical fitness/recovery capabilities. Mental/emotional wellness and resiliency contributes to cognitive throughput and performance during high-gain missionized tasks. Conversely, a lack of balance and emotional stability hinder reasoning and effective task management. Total flight time and Mission-Design Series (MDS) specific experience in a particular aircraft or system increases operator situation awareness (SA) and performance. In 2000, F-15J fighter pilots from the Japanese Air Self-Defense Force (JASDF) demonstrated that an increase in total flight time was directly proportional to an increase in cerebral oxygen status (COS) during high-G maneuvering, aiding their ability to combat the risks of G-Induced Loss of Consciousness (G-LOC). This phenomenon has plagued pilots in aviation-related fatalities for decades since the arrival of high-G capable aircraft and is caused by the reduction in cerebral blood flow and oxygen supplied to brain tissues (Kobayashi, Tong, & Kikukawa, 2002). One acceptable method of obtaining COS measurements is through Near-Infrared Spectroscopy (NIRS) which includes non-invasive readings of pre-frontal oxygenated hemoglobin in the brain from light wave propagation measurements (Kobayashi et al., 2002). Lastly, physical fitness and recovery capability play an integral part in human capacity for physical exertion and sustainment under multi-axial accelerations. Fatigued muscles in fighter pilots are more susceptible to acute injuries, and they are not as capable of supporting the spinal column as effectively as unfatigued muscles (Sovelius, Oksa, Rintala, & Siitonen, 2008).

Second, *environmental inputs* represent the changing conditions an operator undergoes over the course of a mission due to mission tasks. Environmental inputs consist of gravitational forces (Gs), thermal stress, oxygen consumption (VO_2) rate, and ambient light as seen in Figure 2. A specific mission task, such as aerial combat, leads to an increase in Gs on the body, which is an example of a dynamic environmental input.

Third, gravitational suits (G-suits), upper pressure garments (UPGs), pressure breathing under G (PBG) equipment, flight suits, gloves, and helmet visors are all examples of *operator compensation*. These articles help the pilot fight through challenges due to fluctuating environmental inputs and are denoted by the compensator block in Figure 2.

Fourth, *performance* is the operator's output from Figure 2 and characterized by the "open-loop response" of environmental inputs, operator compensation, and operator state. The mission-driven operator-compensated (MDOC) system in Figure 2 is a function of the fluctuating inputs, compensation, and state.

Next, *performance enhancement* projects what performance output a human pilot is capable of achieving when the feedback loop is closed and the operator is fully cognizant of current inputs, compensation, and PC state. This augmentation has the potential to increase overall SA through the use of biofeedback.

2.4 Biofeedback

Biofeedback is a mind-body aid that uses electronic sensors to measure physiological processes and help individuals gain a better understanding and control over normally automatic bodily functions (Gilbert & Moss, 2002). Biofeedback instruments track metrics such as: HR, heart rate variability (HRV), respiration, muscle activity, skin temperature, blood pressure, brain activity, and COS. Research has shown that biofeedback is beneficial in treating a number of behavioral, attention, and medical challenges (Yucha & Gilbert, 2004). The concept of using biofeedback techniques in aviation systems has been introduced, but not to aid in human performance and PC state recognition, rather in pilot vehicle interface (PVI) design. In 2000, the Air Force Research Laboratory (AFRL) introduced the concept that pilot choice (gaze point) could be identified through dominant frequency electroencephalographic (EEG) patterns of visually evoked brain activity. An eye gaze-based control would facilitate a simpler PVI design with less mechanization. These gaze patterns could be refined and brought under voluntary control through biofeedback training (Calhoun, 2000).

The reason biofeedback has gaining little momentum in operator PC state recognition applications stems from the inherent challenges that exist with taking accurate measurements and rapidly processing data to a real-time display during flight. However, as advances in biosensor technology size, processing speed, and accuracy continue, the avenue is open for future research.

2.5 Operator Measurement

As previously discussed there are a myriad of factors that affect operator PC state throughout the dynamic flight environment. Additional complications exist regarding measurement of physiological metrics from locations on the human body during flight. Cockpit ergonomic design, electromagnetic interference (EMI), aircrew flight equipment (AFE), thermal stress, perspiration, and multi-axis acceleration forces all present difficult challenges to correctly measure changes to the “pink squishy bag” known as a human body.

2.5.1 Cardiac Metrics

Various heart measurement techniques exist today that support a multitude of disciplines from medicine to professional athletes. The most widely used type of heart monitoring device is the electrocardiogram (ECG), which functions by placing electrodes on the human chest to measure electrical activity. By comparing inter-beat intervals a single HR value can be generated in beats per minute (BPM). Recent studies demonstrated that a measurement of the low-frequency spectral power (LF) to high frequency spectral power (HF) ratio of the HRV spectrum could be used as a predictive tool in gauging operator psychophysiological load. The critical HRV metric, which reflects the statistical variability of heart rate (Cacioppo, Tassinary, & Berntson, 2007), had a significantly higher ratio of LF/HF recorded during flight compared to pre-flight and post-flight conditions of 59 cadets of the Air Force Military Academy, in Deblin, Poland (Skibniewski et al., 2015).

2.5.2 Respiratory (O_2 / CO_2) Metrics

Development of the Aircrew Mounted Physiologic Sensor Suite (AMPSS) has been an ongoing effort by AFRL and the 711th Human Performance Wing (711 HPW) at Wright-Patterson AFB, OH. The vision of AMPSS is to incorporate sensors on AFE equipment to allow real-time monitoring of breathing gas delivery and in-flight measurement of aviator respiratory parameters. The sensor suite includes respiratory, aircraft breathing gas, and cabin environmental sensors. Current models are compatible with existing gear, while the program end-state includes full integration into AFE and fighter-type aircraft.

Future benefits to the warfighter will be seen through a real-time monitoring of respiratory state, which will enhance training and mitigate risks associated with breathing gas delivery failure, pilot hypoxia, and cardiorespiratory stress. Through the use of smart algorithms developed to monitor and assess pilot stress and performance, sensing could be integrated into aircraft warning/alerting systems. Based on a perceived debilitated cardiorespiratory state, progressive levels of alerting could lead to operator augmentation, and ultimately automation intervention if a pilot became incapacitated.

A previous AMPSS iteration 2.0 was used as part of a United States Air Force Test Pilot School (USAFTPS) 14B Test Management Project (TMP) named HAVE

BREATHLESS. The design was intended to offer a minimally invasive means to capture real-time operator breathing state through a modification to the existing MBU-20/P flight mask (Schmitt, Makover, Elliott, McDonald, & Koeniguer, 2015).

AMPSS 2.5 as seen in Figure 3, capitalized on much of the same hardware as AMPSS 2.0, which facilitated measurement and collection of subject oxygen (O_2)/carbon dioxide (CO_2) pressures and mass flow rates. AMPSS 2.5 was used in Phase 1 of this research as well as the USAFTPS TMP HAVE PUFFIN tested by members of class 16B. AMPSS 2.5 included minor modifications to reduced size and increase functionality. All AMPSS models have been tested in support of research by the 711 HPW.

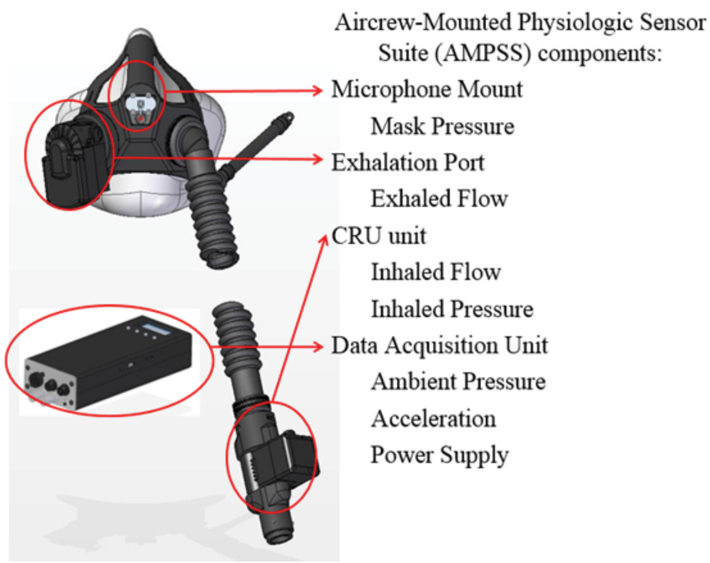

Figure 3: AMPSS 2.5 Layout

AMPSS 3.0 as seen in Figure 4 is a completely new unit from previous versions in an attempt to greatly decrease weight while increasing user comfort and system functionality. The system is designed to collect partial pressure of oxygen, breathing flow volume and rate, pressure, temperature, humidity, cabin pressure and temperature, and acceleration. The device runs on an internal 9V Lithium battery and stores data on a micro SD card. Hardware is mounted in line between the CRU-60/P regulator and the subject's oxygen breathing hose. AMPSS 3.0 was used in Phases 3 and 4 of this research.

Figure 4: AMPSS 3.0 - Mounted in line with CRU-60/P regulator and oxygen hose

2.5.3 Electroencephalography (EEG) / Forehead Oximetry

EEG is a means of measuring brain activity from voltage amplitude between two electrodes placed on the scalp (Kropotov, 2009). In 2009, the Operator Performance Laboratory (OPL) at the University of Iowa demonstrated that increased EEG activity showed a strong correlation to high workload levels experienced by pilots in a simulated close-air-support (CAS) scenario (Schnell et al., 2009). Measured EEG frequencies not only increased with workload, but the wave pattern correlated with a moment of decision. A decrease in EEG amplitude during high workload frequency peak, indicates impaired decision-making (National Aeronautics and Space Administration, 1987). Future research as part of the P2CP program will look to leverage and incorporate EEG capabilities into a real-time displayed operator state.

2.6 Operator Workload and Exertion

2.6.1 Subjective Workload Measures

Quantifying pilot workload and its effect on human performance has been a challenge for aviation researchers for years. *Workload* is defined as the integrated physical and mental effort required to perform a specified pilot task (Hodgkinson, 1999). Subjective workload measures are typically gathered as self-reports using common scales such as the Bedford Workload Scale (BWS) (Roscoe & Ellis, 1990) or National Aeronautics and Space Administration Task Load Index (NASA-TLX) (Casner & Gore, 2010). The use of paired-comparisons such as the Analytic Hierarchy Process (AHP) and the Subjective Workload Dominance (SWORD) technique have identified different levels of workload between flight phases when other methods did not (North Atlantic Treat Organisation, 2005). Although popular, subjective workload assessments lack unbiased procedures.

Seen in Figure 5, the BWS offers simplicity for operators who follow a hierarchical decision tree to give a rating from 1 to 10. This takes minimal time, which is an advantage if performing the assessment in flight. The disadvantage of the BWS is the task must be completed before a rating can be assigned, and operator attention must be free to focus on paper or displays. Additionally, as operator proficiency increases, they tend to skip the hierarchical tree and immediately generate a numerical score (Casner & Gore, 2010). BWS was developed to be a “domain-specific” rating metric aimed towards capturing workload and cognitive strain only. However, coupled effects can occur in tests involving physiologically demanding tasks (dependent on subject environment and task), and yield BWS scores that fail to capture solely workload.

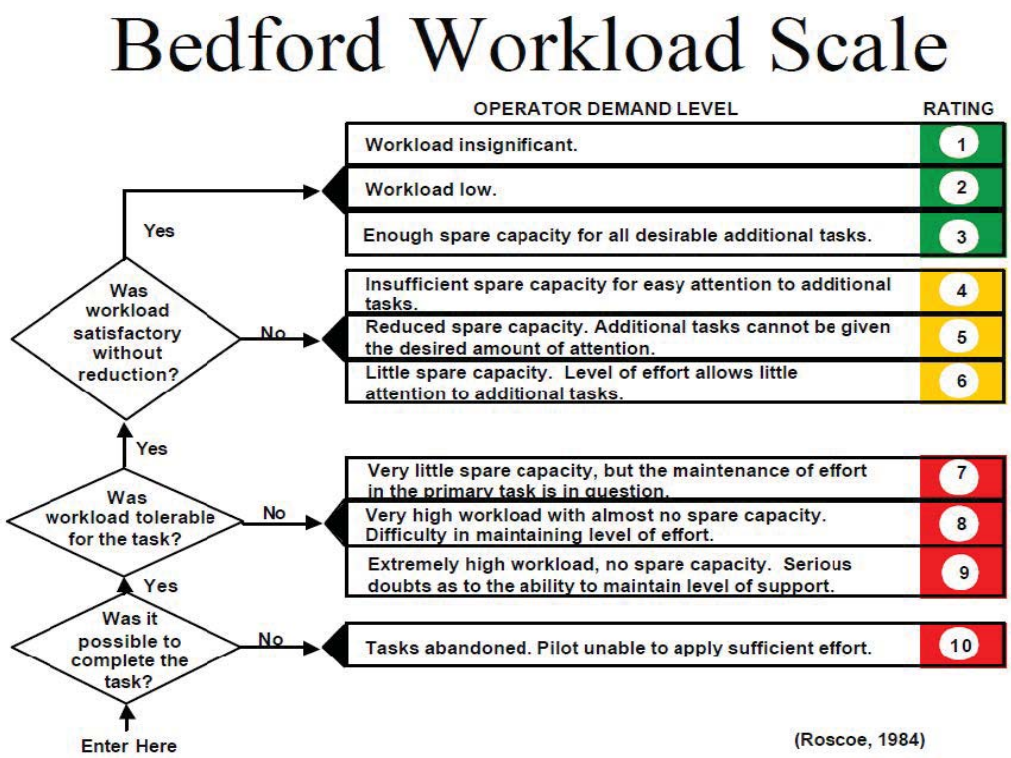

Figure 5: Bedford Workload Scale (Roscoe & Ellis, 1990)

The NASA-TLX offers a blend of six sub-scales, which capture: mental, physical, temporal demand, performance, frustration, and effort. Since individual definitions of workload vary by placing different emphasis on these metrics, combining the sub-scales into a total weighted score accommodates the different ways of conceptualizing workload among subjects. The NASA-TLX scale also allows verbal collection and can be done either mid-task or post-task. However, collection can be time consuming and may affect operator performance if completed mid-task (Casner & Gore, 2010).

2.6.2 Objective Workload Measures

Objective workload measures involve some type of data collection done on the operator or their environment and can be broken down into three sub-classes: (1) process input, (2) performance, and (3) physiological. First, process input metrics capture any inputs performed by an operator to the system. Examples of this include the displacement an operator moves a device, lever, knob, or flight control while attempting to track a specific objective. Second, performance metrics capture outputs from the system. Examples include operator ability to track a specific objective (airspeed, bank angle, altitude, or G) while minimizing errors between the intended versus actual output. Third, the following physiological metrics collect sensory data from the operator PC state and dynamic environment: ECG, EEG, COS, pulse oximetry, ocular response, galvanic skin response, and respiratory response (Engler et al., 2013). Ideally, physiological workload metrics allow unobtrusive measurements to be taken from operators, eliminating the need for secondary tasks or verbal opinions. Unfortunately, different individuals display varying physiological responses to workload, so no all-encompassing physiological index has been constructed yet (Casner & Gore, 2010).

Varying operator capabilities captured by the uniqueness of PC state may initially mask increased pilot workload. However, once PC overload occurs, the result is degraded performance. Quantifying any excess cognitive capacity of a pilot is challenging and requires attempting to measure workload via the aforementioned subjective and objective techniques.

2.6.3 Borg Rating of Perceived Exertion (RPE) Scale

Classification of effort ratings of humans at work is neither simple nor trivial. Health professionals recognize the importance of understanding the correlation between patient physical working capacity and subsequent subjective symptoms and strain. Perceived exertion is arguably the single best indicator of the degree of physical strain. High correlations exist between perceived exertion and heart rates as well as peripheral factors such as blood lactates. In 1970, Borg constructed a Rating of Perceived Exertion (RPE) scale under the foundation that oxygen consumption and HR increase linearly with workload and exercise intensity. The scale, which has been translated into many different languages, contains values ranging from 6 to 20 (notionally denoting heart rates ranging from 60 to 120 BPM). A modified scale with ratio properties seen in Figure 6 below was amended to a range from 1 to 10 and is widely used today. Of note, the Borg RPE scale is a "domain-specific" rating metric aimed towards capturing physiological strain only.

1 - 10 Borg Rating of Perceived Exertion Scale	
0	Rest
1	Really Easy
2	Easy
3	Moderate
4	Sort of Hard
5	Hard
6	
7	Really Hard
8	
9	Really, Really, Hard
10	Maximal: Just like my hardest race

Figure 6: Borg Rating of Perceived Exertion (RPE) Scale

2.7 Heart Rate (HR) and Percent Heart Rate Reserve (%HRR)

Biometrics such as HR, %HRR, and HRV have proven effective metrics for determining physiological activity and workload. A human HR, measured in BPM by sensors that sample/record once per second, is the oldest physiological workload metric.

While a worthy parallel to physical activity, HR is only a fair correlate to mental activity. The HRV metric is defined as the difference in the time intervals between heart beats, irrespective of the number of BPM (Casner & Gore, 2010). A Finnish Air Force study found that comparisons of HR and HRV can differentiate varying task demands and workload levels in situations where performance variations were negligible (Mansikka, Virtanen, Harris, & Simola, 2015).

Flight test efforts supporting the F-22 Life Support Systems Task Force identified %HRR as a potential predictive indicator of exertional fatigue during the performance of high G maneuvers (F-22 Life Support System (LSS) Independent Analysis, 2012). %HRR is a constantly changing value based on current HR and defined on a percentage scale (0 to 100) as the amount of heart rate capacity that a subject is currently using. The scale is individualized based on a specific subject's maximum HR (HR_{max}) and resting HR (HR_{rest}). A %HRR value of 90 would indicate that a subject was using 90% of their HR capacity and probably point to a noticeably exerted subject. Specifically defined by Equation 1 below, %HRR is defined as the percent difference between current HR capacity over total HR capacity.

$$\%HRR = \frac{HR - HRrest}{HRmax - HRrest} \quad (1)$$

Correlations have been drawn by the U.S. Department of Health and Human Services between %HRR, workout intensity level, and Borg RPE. Additionally, %HRR has been correlated to VO_2, which is discussed further in this chapter. The RPE scores listed in Figure 7 below, taken from the Physical Activity and Health: Report of the Surgeon General in 1996, are in accordance with the traditional 6 to 20 Borg scale, notionally aligned with HR values of 60 to 200 BPM discussed previously in this chapter.

Focusing on the first three columns below, very light workout intensity and RPE scores below 10 traditionally correlate to %HRR and VO_2 values of less than 20%. As intensity increases to very hard and maximal intensity, %HRR/VO_2 values increase beyond 85% correlating to RPE scores of 17 to 20 (170 to 200 BPM). While these relationships are not always steadfast, they do provide a strong link between %HRR, Borg RPE, and workout intensity (Physical Activity and Health: A Report of the Surgeon General, 1996).

Classification of physical activity intensity, based on physical activity lasting up to 60 min.

	Endurance-type activity							Resistance-type exercise
	Relative Intensity			Absolute intensity (METs) in healthy adults (age in years)				Relative Intensity*
Intensity	VO_2R (%) heart rate reserve (%)	Maximal heart rate (%)	RPE†	Young (28–39 yr)	Middle-aged (40–64 yr)	Old (65–79 yr)	Very old (80– yr)	Maximal voluntary contraction (%)
Very light	<20	<35	<10	<2.4	<2.0	<1.6	≤1.0	<30
Light	20–39	35–54	10–11	2.4–4.7	2.0–3.9	1.6–3.1	1.1–1.9	30—49
Moderate	40–59	55–69	12–13	4.8–7.1	4.0–5.9	3.2–4.7	2.0–2.9	50–69
Hard	60–84	70–89	14–16	7.2–10.1	6.0—8.4	4.8–6.7	3.0–4.25	70–84
Very hard	≥85	≥90	17–19	≥10.2	≥8.5	≥6.8	≥4.25	≥85
Maximal‡	100	100	20	12.0	10.0	8.0	5.0	100

Table 1 provided courtesy of Haskell and Pollock.
*Based on 8–12 repetitions for persons under age 50–60 years and 10–15 repetitions for persons aged 50–60 yr and older.
†Borg rating of Perceived Exertion 6–20 scale (Borg, 1962) (24).
‡Maximal values are mean values achieved during maximal exercise by healthy adults. Absolute intensity (METs) values are approximate mean values for men. Mean values for women are approximately 1–2 METs lower than those for men; VO_2R = oxygen uptake reserve.
Adapted from and reprinted with permission from U.S. Department of Health and Human Services: *Physical Activity and Health: A Report of the Surgeon General*. Atlanta: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, 1996 (242).

Figure 7: %HRR and VO_2 Indices By Workout Intensity
(Physical Activity and Health: A Report of the Surgeon General, 1996)

2.8 Exercise, Energy Transfer, and the Oxygen Transport System

Physical activity generates a great demand for energy transfer in the body. Immediate energy, at the onset of a power lift, brisk walk, or sprint is generated almost exclusively from high-energy phosphate sources like adenosine triphosphate (ATP) (McArdle, Katch, & Katch, 2015). After initial consumption, short duration energy requires immediate resynthesis of depleted ATP. This process is fueled by anaerobic glycolysis, stored muscle glycogen breakdown, and results in lactic acid accumulation in blood and muscles. During light to moderate activity, lactate disappearance matches formation and most ATP energy is still generated from oxygenated hydrogen. As exercise intensity increases lactic acid, which accumulates faster in untrained athletes compared to trained athletes, builds ultimately generating a localized "tissue hypoxia". An average human shows an exponential lactic acid increase around 50-55% maximal aerobic capacity (McArdle et al., 2015).

Energy transfer for long-term endurance is predominately a function of aerobic capacity and lactate removal rate, which is dominated by the oxygen transport system. The oxygen transport system consists of pulmonary ventilation, hemoglobin concentration, cardiac output, peripheral blood flow, and cellular metabolism. Individual VO_2 is the rate oxygen is consumed by volume, measured in mL per kg per minute. This metric captures the ability to supply, transport, deliver, and use oxygen. Endurance athletes can perform at a steady-state of 80-90% of their maximal aerobic capacity predominately due to superior rate of lactate removal and VO_2 (McArdle et al., 2015).

2.8.1 Maximal Oxygen Consumption (VO_{2max})

Maximal oxygen consumption (VO_{2max}), or maximal oxygen uptake, is reached in extreme high intensity exercise when oxygen consumption plateaus and maximal aerobic power is attained. This metric provides a quantitative measure for the capacity for aerobic ATP resynthesis and indicates how well an athlete can maintain intense physiological activity. A high VO_{2max} demands integrated high-level response of the oxygen transport system.

2.9 Chapter Summary

This chapter set the necessary framework for this research by covering a review of literature spanning fields of human physiology, human-machine systems, PC biosensors, workload, and human performance, and biofeedback. First, definitions for operator PC state, compensation, performance, and enhancement were explained to facilitate a better understanding of an MDOC system. Next, capabilities and limitations to operator PC measurements in flight were discussed. Third, both subjective and objective measures for workload were addressed and critiqued. Fourth, the importance of HR, HRV, and %HRR was highlighted as a proven and effective measure of operator physiological workload levels. Lastly, a brief description of the oxygen transport system was provided and VO_{2max} was defined. Chapter 3 explains the materials, equipment, and experimental design supporting the research methodology.

3. Research Methodology

3.1 Chapter Introduction

This chapter will describe the primary materials, equipment, data collection processes, and overall methodology used to achieve research objectives. The first section of this chapter highlights the theory as well as novelty of this research, while reaffirming basic terminology introduced in Chapter 2. The second section identifies specific test objectives (STOs) and measures of performance (MOPs), which helped form the cornerstone of the research methodology. Third, the system under test (SUT) and test roles and responsibilities are outlined. Fourth, each phase is thoroughly detailed and broken down by materials and equipment as well as test and evaluation (T&E) procedures. Lastly, testing resources are listed and limitations and constraints are identified which impacted test conduct.

3.2 Theory

This research spans fields of human physiology, biofeedback, human-machine systems, PC sensors, workload, and human performance. An operator PC state is affected by both short term (nutrition/hydration, sleep, currency/training) and long term (mental/emotional wellness, experience, physical fitness/recovery) influences. When combined with operator compensation methods and mission-driven changes to the operational environmental, performance is the result. In order to enhance individual awareness of PC state, biofeedback tools must be in place to measure PC changes in operators. High performance aircraft cockpits present many challenges in accurately measuring operator PC fluctuations. The novelty of this research leveraged accurate PC measurements, while focusing solely on cardiac biometrics. Through a sequential approach that commenced with basic hardware testing and culminated with airborne augmentation, this research was targeted specifically at enhancing pilots in high performance aircraft by providing a valid real-time heart rate (HR) biofeedback solution to the operator. The following research question was the driving force behind this methodology:

How can a real-time biofeedback visualization of operator physiological and cognitive state enhance awareness, decision-making, and performance?

3.3 Specific Test Objectives (STOs) and Measures of Performance (MOPs)

This research was conducted in four primary phases as seen in Table 2 below and outlined in the following sections of this chapter.

Table 2: Specific Test Objectives (STOs) and Measures of Performance (MOPs)

Phase 1 (C1)	**Initial hardware and subject centrifuge trials**
	STO 1: Assess initial hardware and test profile
	MOP 1: Cardiorespiratory response
	MOP 2: Tracking performance
	MOP 3: Workload Level
	MOP 4: Hardware accuracy
Phase 2 (L1)	**Laboratory VO_{2max} testing**
	STO 2: Determine operator peak physiologic output
	MOP 1: Maximal Oxygen Consumption (VO_{2max})
Phase 3 (C2)	**Training and build-up approach centrifuge testing**
Phase 4 (F1)	**Flight testing**
	*Combined STOs and MOPs for phases 3 and 4
	STO 3: Determine operator PC state
	MOP 1: Percentage Heart Rate Reserve (%HRR)
	MOP 2: Portable ECG Unit (PECGU) Accuracy
	MOP 3: Cognitive State
	STO 4: Determine the effect of providing biofeedback on operator PC state awareness
	MOP 1: Awareness of PC state without %HRR biofeedback
	MOP 2: Awareness of PC state with %HRR biofeedback
	STO 5: Determine effect of providing biofeedbaack on decision-making
	MOP 1: Decision-making without %HRR biofeedback
	MOP 2: Decision-making with %HRR biofeedback
	STO 6: Determine effect of providing biofeedback on tracking performance
	MOP 1: Centrifuge tracking task accuracy without biofeedback
	MOP 2: Centrifuge tracking task accuracy with biofeedback
	MOP 3: Airborne G-tracking accuracy without biofeedback
	MOP 4: Airborne G-tracking accuracy with biofeedback
	STO 7: Evaluate human system integration of biofeedback display into fighter cockpit
	MOP 1: Usability of display
	STO 8: Collect Aircrew Mounted Physiologic Sensor Suite (AMPSS 3.0) Data

Materials, equipment, data collection, and evaluation methods varied based on phase and STOs, but predominantly provided consistency between phases. The T&E was structured using a build-up approach to testing and is meant to directly support STOs.

3.4 System Under Test (SUT)

The primary SUT was a human subject. The test subjects for Phase 2 laboratory maximal oxygen consumption rate (VO_{2max}) testing ran on a treadmill. The test subject for all Phase 1 and Phase 3 centrifuge testing was the sole occupant of the centrifuge gondola. The test subject for all flight tests was the Test Pilot (TP) and Aircraft Commander (AC) seated in the front cockpit (FCP). A complete picture of all test items worn by the test subjects is illustrated in Figures 8 and 9 below. Additionally, each hardware piece of the system under test is further described in the following sections, broken down by phase.

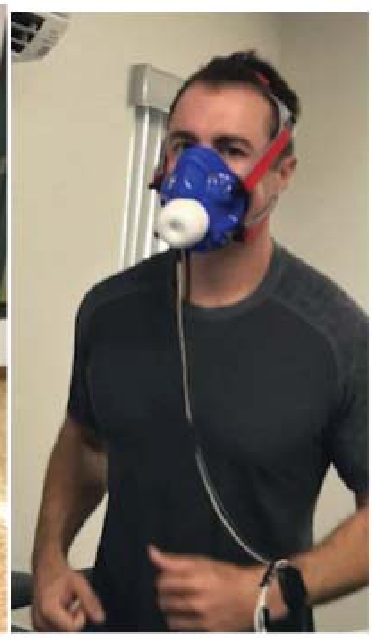

Figure 8: Phase 1 Configuration **Phase 2 Configuration**

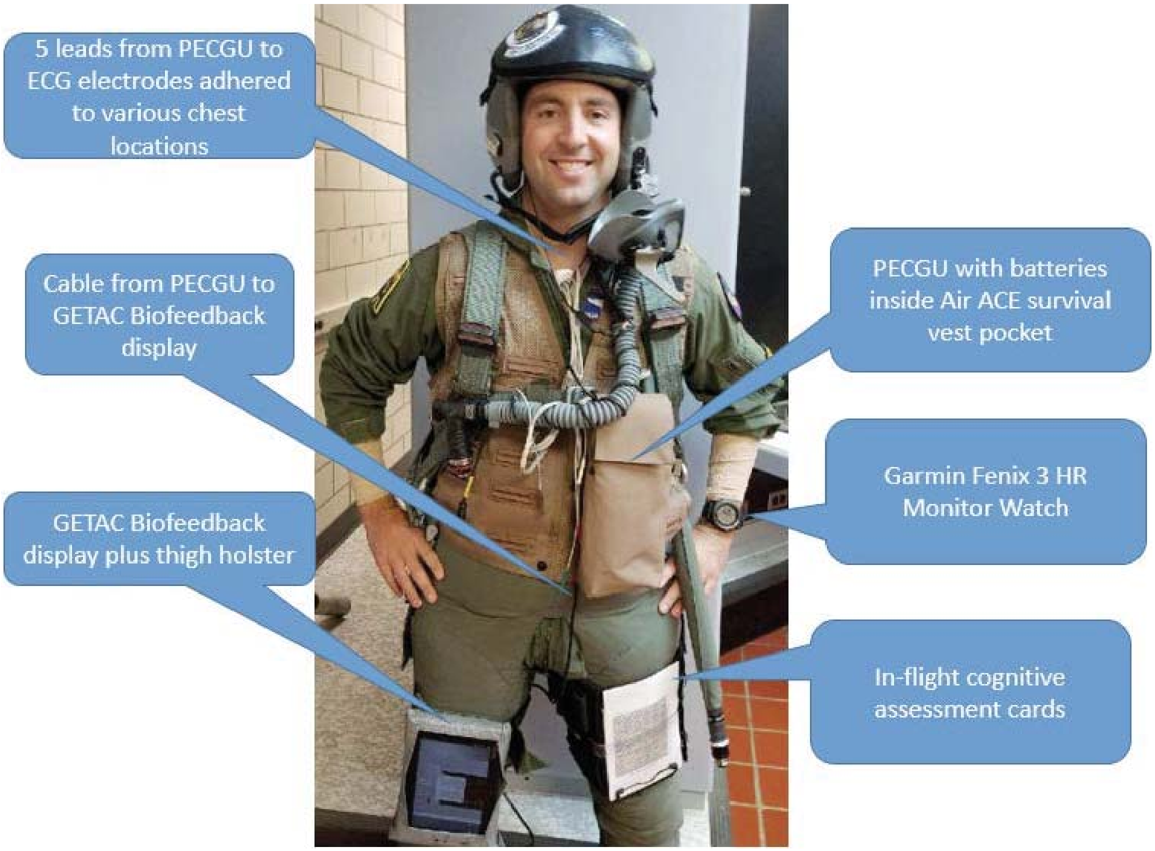

Figure 9: Phase 3 and 4 Configuration

3.5 Test Roles and Responsibilities

At a minimum, execution of tests required a test subject, Test Director (TD), and Test Conductor (TC).

3.5.1 Test Subject

The test subject wore the combined Portable Electrocardiogram Unit (PECGU)-GETAC system and was the individual undergoing physiological monitoring for a particular test (flight or centrifuge). During centrifuge testing the test subject was the sole occupant of the centrifuge gondola. During flight test the test subject was also the TP and AC.

3.5.2 Test Director

The TD was located in the United States Air Force Test Pilot School (USAFTPS) Control Room during flight test and Wyle control room during centrifuge testing. The TD was responsible for the overall safe, effective, and efficient execution of the test. Responsibilities included briefing the safety plan, communications plan, test cards, overall test conduct, and debrief. The TD was the primary team member responsible for timing test runs and rest periods, G-tracking, and administering cognitive testing to the test subject over intercom from the control room.

3.5.3 Test Conductor

The TC was responsible for timing individual cognitive tests, recording results, and overall test conduct of the mission during phases and leading up to the test runs. This provided additional redundancy of data collection for the TD. During flight test, the TC occupied the RCP. During centrifuge tests the TC sat next to the TD in the control room.

3.5.4 Aircraft Commander (AC) / Test Pilot (TP)

The TP was the AC and responsible for safe test execution, and correct performance of the flight test techniques (FTTs) used during flight. The TP briefed sortie administrative items and debriefed areas related to flight safety, flight test execution, and lessons learned. Additional responsibilities included general airmanship, compliance with all applicable guidance and directives, and data collection in the form of surveys and comments. This role was only performed during flight test.

All team members (in flight or control room) were responsible for monitoring of the test subject for signs of excessive fatigue or adverse physiological symptoms. Any team member could initiate an abort, cancel further testing, and recommend return to base (RTB).

3.6 Phase 1 (C1): Initial Hardware and Subject Centrifuge Trials

Phase 1 was supported by the aid of KBRWyle Science, Technology and Engineering Group (KBRWyle) at Brooks City-Base (BCB) in San Antonio, TX from 1 to 4 November 2016. Seven test subjects from the High-G Acceleration Human Subject Panel (HGAHSP) at BCB (referred to as Subjects 1 through 7) were used to evaluate several initial proposed HR collection hardware configurations and assess the planned test profile. During trials subjects were required to participate in tracking tasks that consisted of manipulating a flight control stick while tracking a target in a flight simulator. A detailed description of the tracking task is provided in the Phase 1 T&E section below.

HGAHSP subjects are volunteer members that participate in monthly centrifuge testing. Level of experience varies. Centrifuge exposure and G proficiency is greater than the average high performance aircraft operator, but tracking task proficiency is lower than the average operator. HGAHSP subjects were only used in Phase 1 testing and were not part of USAFTPS 17A HAVE HOPE Test Management Project (TMP) team.

3.6.1 Phase 1 Materials and Equipment

All subjects were outfitted with aircrew flight equipment (AFE) gear consisting of the following: flight suit, HGU-55/P flight helmet, MBU-20/P oxygen mask, and CSU-23P Advanced Technology Anti-G Suit (ATAGS). Additionally, KBRWyle ECG leads were attached to the test subject chest to provide a "truth source" of HR data. A detailed description of the hardware used is included in the following sections.

3.6.1.1 Portable Electrocardiogram Unit (PECGU)

A custom designed Portable Electrocardiogram Unit (PECGU) prototype with associated hardware and software developed by the 711 HPW was the primary hardware under test for this phase. The PECGU seen in Figure 10, incorporating the Analog Devices ADAS1000 ECG board, is a multiple channel system for measuring ECG, pace, and respiration signals, with programmable digital signal processing filters for noise reduction. The system is used in a 5-lead ECG configuration with adhesive electrodes and sampled at 2 kHz. The ECG signal is packaged by a Systems Demonstration Platform with a SDP-B processor and outputs using a USB 2.0 cable. The system was not capable of recording and storing ECG data without further modification. For the purposes of this test, ECG data were used to measure raw HR for calculation and display of percentage heart rate reserve (%HRR) in future phases.

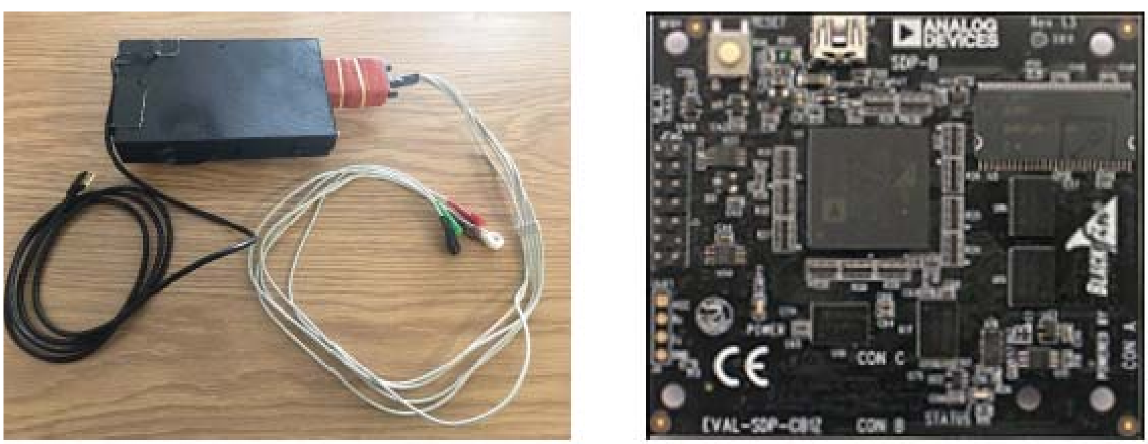

Figure 10: Portable Electrocardiogram Unit (PECGU)

3.6.1.2 AMPSS 2.5

The Aircrew Mounted Physiologic Sensor Suite (AMPSS) 2.5, a suite of sensors installed to the MBU–20/P aircrew mask and oxygen delivery hose, was used to measure subject breathing airflow rate and pressure changes. The vision for this technology was to provide real–time, in–flight monitoring of pilot physiology. Seen in Figure 11 below, AMPSS 2.5 served as an aerospace research tool in centrifuge, altitude chamber and aircraft flight environments (Thorn, Bartee, Buell, Goh, & Mastracchio, 2017). The AMPSS 2.5 system consisted of a MBU–20/P modified mask exhale valve and an in–line inhalation sensor. Further information on AMPSS and prior testing is outlined in Chapter 2.

Figure 11: AMPSS 2.5 - Modification to MBU-20/P Flight Mask

3.6.1.3 Zephyr BioHarness 3.0

A Zephyr BioHarness 3.0 (Zephyr) chest strap was used to measure subject HR, ECG, and breathing rate. The BioHarness 3.0 is a physiological monitoring telemetry device consisting of a chest strap and an electronics module that attaches to the strap. The device stores and transmits vital sign data including ECG, heart rate, respiration rate, body orientation and activity. Seen in Figure 12 below, the BioHarness 3.0 provides a facility to detect and transmit single lead ECG signals to be received by USB qualified ECG instruments (Zephyr, 2012).

Figure 12: Zephyr BioHarness 3.0 HR monitor chest strap

3.6.1.4 Elbit Systems Canary Pilot Health Monitoring System

The Elbit Systems Canary Pilot Health Monitoring System (Elbit) seen in Figure 13 below was used to measure subject HR. The Elbit introduced a miniature sensing platform to the standard HGU-55P helmet shell to produce an integrated, non–invasive cardiovascular monitoring system. This miniature sensing platform was integrated in the helmet's forehead edge roll (covering forehead) and included several electro-optic sensors that produced a signal derived from pulsatile cerebral blood flow. A Miniature Dynamic Light Scattering (MDLS) sensor measured cerebral blood perfusion and HR (Thorn et al., 2017).

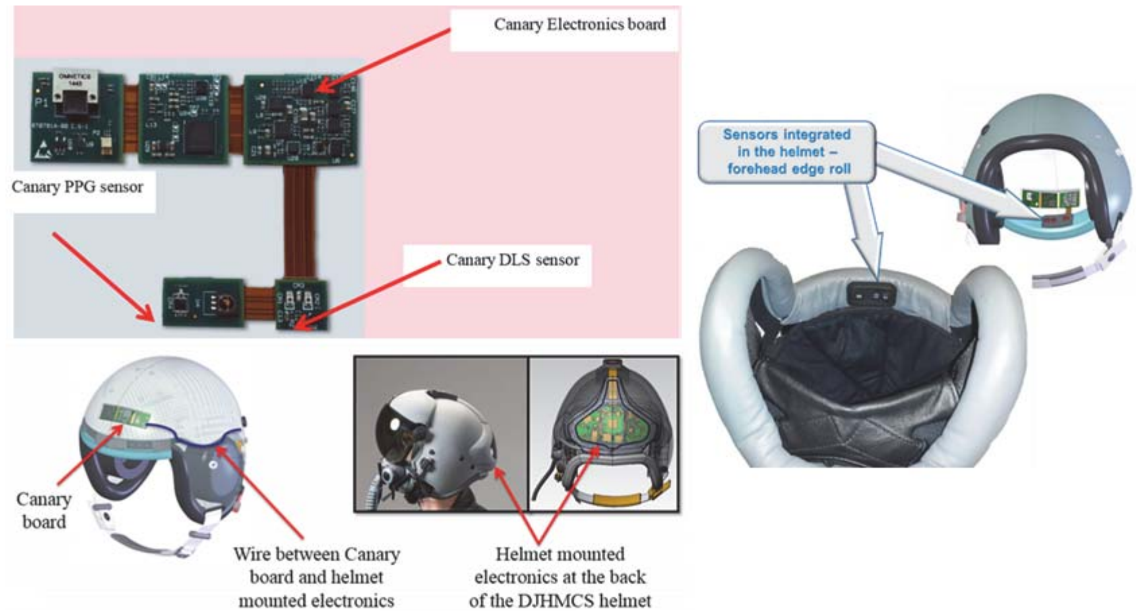

Figure 13: Elbit Layout

3.6.2 Phase 1 Test and Evaluation

As highlighted in Table 2, the STOs for Phase 1 were focused around assessing various hardware configurations for future testing and measuring subject cardio response, workload levels, and tracking performance. The centrifuge test profile in Table 3 below consisting of both loaded (high-G) and non-loaded (low-G) events directly supported these STOs.

Table 3: Phase 1 Centrifuge Profile

G Level	1.4	5	1.4	6	1.4	7	1.4	8	1.4	8-5-3-8-5-3-8-5-3	1.4	9-5-9-5	1.4	00:10:40
Duration (sec)	60	30	60	30	60	20	60	10	60	90 (10 per g level)	60	40 (10 per g level)	60	
Tracking Task	A		B		C		A		B		C		A	

Subjects began the profile at 1.4 Gs, which will subsequently be referred to as low-G because it corresponds to the minimum speed at which a test can be conducted. Once the first low-G event began subjects were required to perform a longitudinal tracking task on X-Plane 10 simulator. With a display mounted inside the centrifuge chamber, subjects had direct control of a gun cross on the display via a side-mounted control stick. Subjects input longitudinal stick forces to hold the displayed gun sight symbol over a target aircraft. Target aircraft drift was generated by a series of sine wave disturbances at randomized frequencies that manifested in lead and lag on the display requiring subjects to continuously make small fine-motor corrections. A sample of disturbed tracking and the X-Plane simulator display is shown in Figure 14 below. The three graphs are an example of three different profiles with random disturbances injected. KBRWyle used these options during Phase 1 and each graph shows a different random profile the subjects attempted to track.

After 50 seconds of tracking, subjects had 10 seconds to provide a subjective scoring of perceived workload from 1 to 10 by using the Bedford Workload Scale (BWS). A score of 1 corresponds to insignificant workload and a score of 10 represents extreme workload in which tasks are abandoned. A discussion of BWS is provided in Chapter 2.

After 60 seconds total, the low-G event was terminated and a high-G event commenced for 30 seconds. During loaded events subjects had no control of G force and no tracking task was required. Once the high-G event was terminated the profile repeated in accordance with Table 3 until the last low-G event and BWS was completed. Tracking task performance was quantified as a percentage of time on target (%TOT) and a root mean square (RMS) error score.

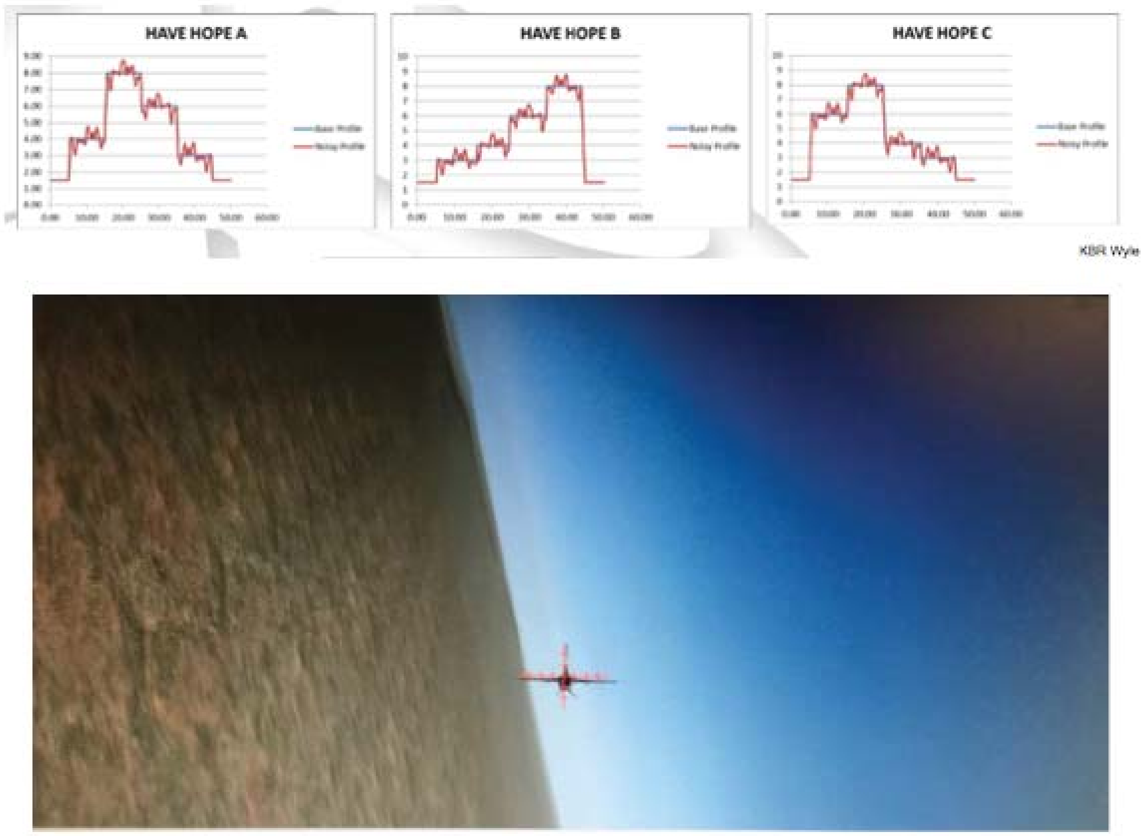

Figure 14: Phase 1 X-Plane Simulator Display with Tracking Task

3.7 Phase 2 (L1): Laboratory VO_{2max} Testing

Phase 2 testing was conducted from 13 to 14 July 2017 at the Physical Therapy clinic at Edwards AFB, CA by trained research team members from the 412th Medical Group. Test administrators were certified to administer a VO_{2max} test. Five test subjects (referred to as Subjects A through E) consisted of members of the USAFTPS 17A HAVE HOPE TMP team. Subjects performed a VO_{2max} test on a treadmill to determine their exercise-base maximum heart rate (HR_{max}).

3.7.1 Phase 2 Materials and Equipment

Five ECG adhesive electrodes were placed along subject chest cavity to measure HR. A standard treadmill was used to conduct the test. A detailed description of additional hardware used is included in the following sections.

3.7.1.1 Portable Metabolic Unit

A Portable Metabolic Unit (PMU) similar to Figure 15 below was used during Phase 2 testing to determine when maximum oxygen uptake had plateaued. PMUs provide precise real-time measurements of human metabolic functions. Accurate measurements can be obtained for inhaled and exhaled oxygen and carbon dioxide, as well as heart rate, temperature, and gas pressure.

Figure 15: Portable Metabolic Unit

3.7.1.2 Garmin Fenix 3 Sapphire HR Monitor Watch (Garmin)

The Garmin Fenix 3 Sapphire HR Monitor Watch (Garmin), seen in Figure 16 below and used in Phase 2, featured a multisport training capability and a built-in optical HR sensor. The HR sensor rested flush with the user’s wrist and could monitor, record, and display real-time HR data. Additionally, a customized colored-coded HR scale based on resting and maximum HR was displayed during high intensity workouts. Zone settings were customizable, but default settings used for this research can be seen in Figure 16 below and included: Zone 1 (0-60%), Zone 2 (60-70%), Zone 3 (70-79%), Zone 4 (79-90%), and Zone 5 (90-100%).

Figure 16: Garmin Fenix 3 Sapphire HR Monitor Watch (Garmin)

3.7.2 Phase 2 Test and Evaluation

As seen in Table 2, the primary STO for Phase 2 was to determine a baseline operator VO_{2max}, peak physiologic output, and corresponding exercise-induced HR_{max} for each subject.

The VO_{2max} protocol adhered to the American College of Sports Medicine guidelines. Subjects were instrumented with a PMU containing a HR monitor. An appropriate jogging or running speed was determined by the test administrator and participant based on the subject's aerobic training, fitness, and comfort. This speed was maintained throughout the duration of the test. Participants were provided with a three-minute warm-up at a slower self-selected jogging speed. Once the test began, speed was increased to the pre-determined speed and the treadmill incline was increased by 2% every two minutes. Cardiorespiratory and metabolic variables were measured and recorded continuously. Borg rating of perceived exertion (RPE) for the subject was recorded every two minutes prior to each inclination increase. The test was continued until the participant reached two of the following VO_{2max} criteria as outlined by the American College of Sports Medicine, Guidelines for Exercise Testing, 9th edition: Plateau in VO_2 despite an increase in workload, Respiratory Exchange Ratio (RER) ≥ 1.1, Borg RPE score ≥ 9 (1-10 scale), and/or HR within 10 BPM of calculated age-predicted (220 BPM – age) HR_{max}. It was also made clear to participants that they had the option to self-terminate the test at any time. Upon reaching termination criteria, the participant would straddle the treadmill as speed was decreased to a slow, comfortable walking speed and incline was returned to level (0%). Recovery lasted at least five minutes and was extended as required until achieving participant pre-test HR value. The HR_{max} was recorded as the exercise-based HR_{max}.

Prior to the VO_{2max} test, each test subject wore the Garmin for one week. Test subjects recorded their HR immediately before bedtime and upon awakening to use as a measure of resting HR (HR_{rest}).

Test subject HR_{max} and HR_{rest} was used to calculate a personalized %HRR that reflected low (<50%), moderate (50-85%), and high (>85%) cardiovascular demands from physical effort. The individualized low, moderate, and high classifications were incorporated into software on the PECGU and displayed in a %HRR biofeedback gauge for Phases 3 and 4.

3.8 Phase 3 (C2): Training and Build-Up Approach Centrifuge Testing

Phase 3 testing was conducted from 14 to 16 August 2017 with the support of KBRWyle at BCB. Subjects A through E from the USAFTPS 17A HAVE HOPE TMP team underwent initial centrifuge training and conducted data collection as a build-up approach for future flight test.

3.8.1 Phase 3 Materials and Equipment

Subjects used the same AFE gear, X-Plane 10 flight simulator, and PECGU as described in Phase 1. Additionally, as described in Phase 2, the Garmin was worn as an additional data source and backup data collection in the event PECGU HR data were lost or the hardware became inoperative. There were some expected noise and system inaccuracies with measuring HR through an optical wrist-mounted sensor instead of traditional ECG leads. A detailed description of new hardware introduced in this phase is included in the following sections.

3.8.1.1 GETAC T800 Tablet

The PECGU was connected to a GETAC T800 tablet with a graphical user interface (GUI) biofeedback display. The GETAC tablet seen in Figure 20 in the Phase 4 section, was a fully rugged tablet with a Windows 10 operating system, 8.1-inch display, and touchscreen capability. The project used a wired-only application and all wireless capability was disabled. The tablet had already passed appropriate airworthiness testing and been used previously in both HAVE CLASSI and HAVE SEXTANT TMPs in F-16Ds at Edwards AFB. The left side of the biofeedback display contained real-time raw ECG outputs. During centrifuge testing, the right side of the display contained a real-time HR output of the subject in beats per minute (BPM).

For the purposes of this Phase 3 testing, PECGU data were used to display just raw HR in BPM on the GETAC T800 tablet using SDP-B software and a built-in GUI.

Modifications were made after Phase 3 and before Phase 4 to output %HRR on the biofeedback display.

3.8.1.2 Thigh Holster

A GETAC holster was worn around the thigh and G-suit of the test subject with a custom mount to allow for real-time viewing as shown in Figure 17 below. The holster had already passed appropriate airworthiness testing and been used in previous TMPs.

Figure 17: GETAC Holster

3.8.1.3 AMPSS 3.0

AMPSS 3.0 as seen in Figure 18 below is a completely new unit from previous versions in an attempt to greatly decrease weight while increasing user comfort and system functionality. During this testing, AMPSS collected partial pressure of oxygen, breathing flow volume and rate, pressure, temperature, humidity, cabin pressure and temperature, and acceleration. The device ran on an internal 9V Lithium battery and stored data on a micro SD card. Hardware mounted in line between the CRU-60/P regulator and the subject's oxygen breathing hose. The AMPSS system was tested as part of an ongoing effort to understand physiological effects and stresses on the operator.

During this research, AMPSS testing was conducted during centrifuge testing only. The system was not incorporated into the biofeedback display.

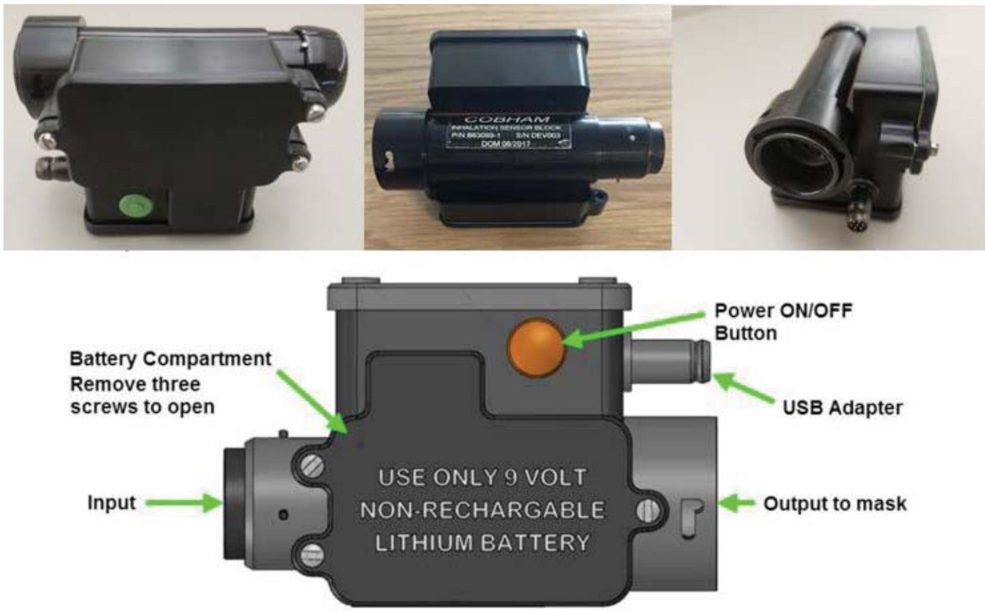

Figure 18: AMPSS 3.0

3.8.2 Phase 3 Test and Evaluation

Phases 3 and 4 were combined and reflect directly back to the overall research question in how real-time biofeedback can enhance awareness, decision-making, and performance. The purpose of Phase 3 centrifuge testing was two-fold. First, as part of a risk reduction and build-up approach test plan, high-G exposure and training was conducted to provide team members with the necessary qualifications to conduct high-G flight test. Second, centrifuge testing provided data in direct support of STOs 3 through 7.

For all profiles, the centrifuge accelerated and decelerated with an onset rate as required to arrive at the next required G-level over a 2 second transition period, to mirror flight test profile execution. The ATAGS pressure was turned on, positive pressure breathing (PPB) was on, and participants performed an anti-G straining maneuver

(AGSM) as individually needed. Termination criteria for all of the centrifuge profiles included completion of the profile, maximum light loss criteria (50% central light loss or 100% peripheral light loss), exhaustion, or if anyone on the research team stopped the test. Special care was made to ensure all testing was in accordance with the Institutional Review Board (IRB) and subjects were not coerced into testing. Each test subject only completed one centrifuge sortie per day.

3.8.2.1 Centrifuge Test Constraints

This paragraph is a prelude to the Phase 4 T&E section and specifically describes the unique differences to centrifuge execution compared to flight test execution. Due to centrifuge system constraints, test subjects were not in direct control of their current G state. A preprogramed test profile was run in the centrifuge that mirrored flight test execution. Test subjects were "along for the ride" as the centrifuge stepped through a series of low-G and high-G planned individual test points and test sets. An example test set is described in Table 4 below and mirrors the same test set for flight test in Phase 4.

Table 4: Sample Test Set (Centrifuge/Flight)

Test Point	Time (sec)
Simulated BFM (6-5-3-8-5-3-8-5-3 +Gs)	106
Cognitive Assessment (Rest)	60 (minimum)
Simulated BFM	106
Cognitive Assessment (Rest)	60 (minimum)
Simulated BFM	106
Cognitive Assessment (Rest)	60 (minimum)
Simulated BFM	106
Cognitive Assessment (Rest)	60 (minimum)

Centrifuge G-tracking was conducted with the same X-plane 10 simulator used in Phase 1. However, Phase 3 tracking was different from Phase 1 in that subjects were performing the task while under G during the "simulated basic fighter maneuvers (BFM)" portion of the test set. Furthermore, the centrifuge tracking task differed to the G-tracking in flight since they were not the same task and total error should not be directly compared.

3.8.2.2 Data Collection Methods and Conditions

HR data was measured from two test equipment sources (PECGU and Garmin), as well a standard ECG HR monitor provided by KBRWyle and considered a "truth source" HR value. KBRWyle HR data was recorded during all centrifuge tests and showed time delineated HR for both with and without biofeedback tests. Since the PECGU could not record and store data, PECGU data was only recorded during with biofeedback tests via the test subjects verbalizing values over intercom. KBRWyle HR was the primary source of HR data for post-flight analysis. The remainder of primary Phase 3 T&E, to include cognitive assessments and the scoring algorithm is described in the Phase 4 T&E section later in this chapter.

3.8.2.3 AMPSS 3.0 Data Collection

AMPSS 3.0 testing in support of STO 8 was conducted on a separate day from primary Phase 3 data collection supporting STOs 3 through 7. Two test subjects wore the AMPSS 3.0, each completing one centrifuge test. The subject configuration during AMPSS data collection consisted of no other Phase 3 test hardware and can be seen in Figure 19 below. Tracking task performance was quantified as a %TOT and RMS error score.

Figure 19: AMPSS 3.0 Data Collection Configuration (Centrifuge Only)

3.9 Phase 4 (F1): Flight Test

Phase 4 testing was conducted from 5 to 18 September 2017 in the R-2508 complex at Edwards AFB, CA with the aid of USAFTPS staff, technical support, aircraft, and facilities. Subjects A through E from the USAFTPS 17A HAVE HOPE TMP team conducted flight test using Data Acquisition System (DAS) equipped F-16DM aircraft, tail numbers 87-0391 and 90-0797. A total of 13 test sorties for a total of 7.4 hours were flown.

3.9.1 Phase 4 Materials and Equipment

Predominantly, Phase 4 materials and equipment mirrored those used in Phase 3. Subjects used the same AFE gear, PECGU, GETAC T800 biofeedback display, and Garmin as described in previous phases. No new hardware was introduced in this phase. Slight modifications were made to existing hardware.

As originally intended, after minor modifications to the biofeedback display after Phase 3, the right side of the display presented a subject-specific %HRR value based on Equation 1. Hence, for the purposes of this phase ECG data were used derive raw HR, convert to %HRR, and display %HRR biofeedback on the GETAC T800 tablet using SDP-B software and a built-in GUI. Seen in Figure 20 below, a scale of %HRR displayed from 0-100% was presented so subjects could view %HRR trends and relative magnitude. Together the PECGU and GETAC display contributed to the biofeedback capability evaluated by the test subject during flight test.

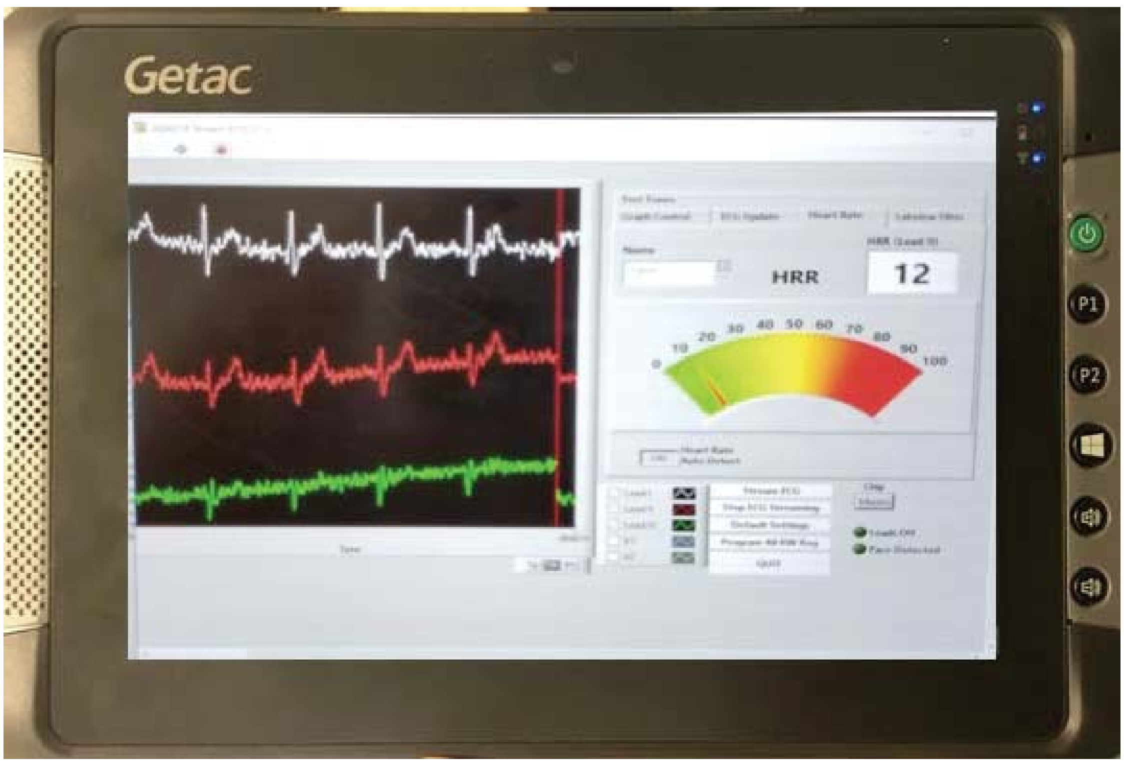

Figure 20: Subject-Specific %HRR Biofeedback Display

3.9.2 Phase 4 Test and Evaluation

Phases 3 and 4 were combined and reflect directly back to the overall research question in how real-time biofeedback can enhance awareness, decision-making, and performance. Flight profiles mirrored centrifuge testing through a series of high-G FTTs, followed by several cognitive assessments. Subjects were augmented with a real-time %HHR biofeedback display to aid in assessing PC state, decision making, and G-tracking performance.

3.9.2.1 Data Collection Methods and Conditions

HR data was measured from two sources (PECGU and Garmin). The PECGU was the primary source of %HRR data fed to the GETAC for real-time biofeedback display. The Garmin was the only recorded HR data source for post-flight analysis.

3.9.2.2 Single Test Set Description

The basic FTT was defined as one test set, which is made up of 9 test points. At the commencement of a test set the test subject maneuvered to a specified G at maximum G onset rate for 10 seconds. Subsequently, the subject would modulate stick force to continue flying a series of “peak and valley” test points intended to simulate a (BFM) engagement. In total, each test set consisted of 9 test points, 10 seconds in duration each. Between test points, a 2 second transition period was used for the test subject to adjust back stick pressure and recapture the next desired G point. Eight transitions occurred and in total a test set lasted 106 seconds (90 seconds + 16 seconds of transition time) in duration and consisted of the test subject executing a 6-5-3-8-5-3-8-5-3 +G series.

3.9.2.3 Complete Flight Profile

A single flight or centrifuge test consisted of 4 fully completed test sets. Figure 21 below highlights an entire flight profile. Figure 22 portrays a detailed description of the PC assessments a subject endured during a single test set. A combination of these two figures can also be found in Appendix A.

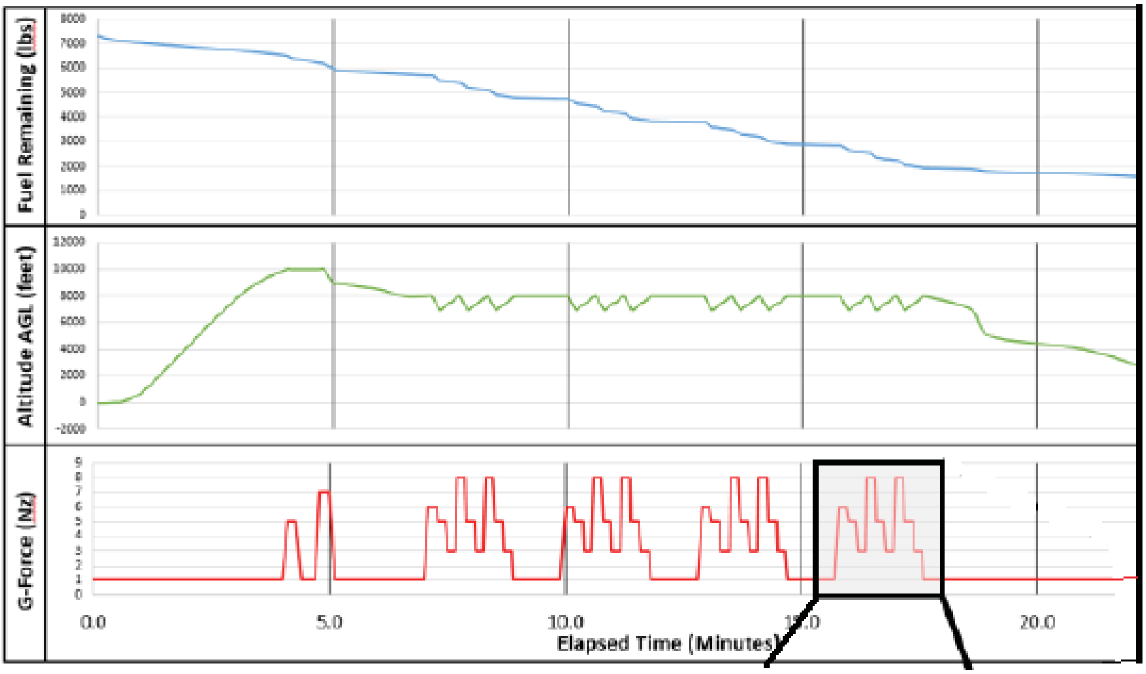

Figure 21: Complete Flight/Centrifuge Profile

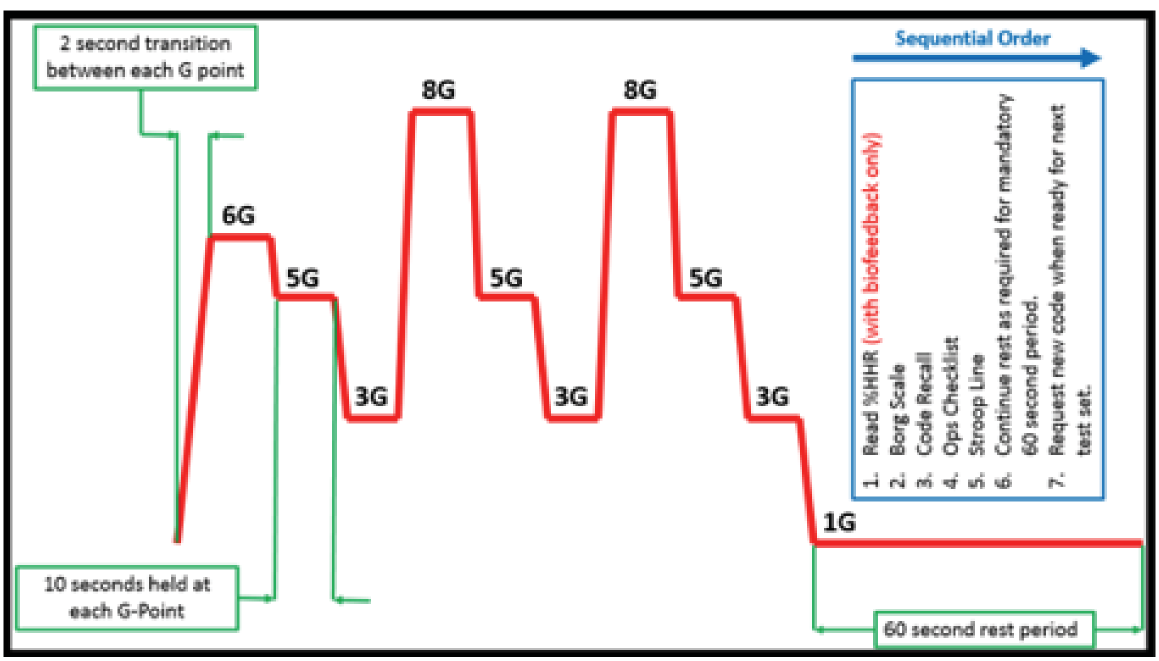

Figure 22: Single Test Set for Centrifuge/Flight (FTT & Cognitive Evaluation)

When biofeedback was provided, test subjects monitored their %HRR on the GETAC display at the termination of high-G maneuvering and beginning of the rest period. Test subjects would verbally acknowledge their %HRR and then monitor as necessary throughout the rest period in order to assist with the rest time duration decision. Prior to each successive test set execution, a timed recording was started and played over VHF radio which contained a 6 second lead in to test set execution. This recording verbally stepped the test subject through each test point and eliminated any variance in timing for test sets.

The TD started and stopped timing at the hack specified on the recording. The TC recorded total rest time between the previous test set termination and next test set execution. The control room team monitored and recorded all time splits for the test subject to complete cognitive assessments described in the following sections.

3.9.2.4 Borg Rating of Perceived Exertion (RPE) Score

Immediately following the high-G portion of the test set (before beginning cognitive evaluations) test subjects reported their Borg RPE Score using the same modified Borg scale (1-10) that was used during Phase 2 laboratory VO_{2max} testing. A full-page version was provided in the test subject flight cards. Additional information and a sample scale of the Borg RPE can be found in Chapter 2.

3.9.2.5 Randomized Code

After Borg RPE was reported, subjects began cognitive evaluations. Prior to the beginning of each test set, the test subject had been directed to memorize a randomized code, five items in length, containing names of shapes, colors, and numbers (e.g., blue, circle, seven, three, five) as seen in Figure 23 below. The code was randomly ordered, with a unique code provided each time. After the Borg score was reported, the TD instructed the test subject to recall the randomized code. The TD recorded the accuracy of the response and the total completion time for the recall task, both contributing to the subject cognitive scores for that test set. This task assessed short-term memory recall and was operationally representative to tasks such as memorizing frequencies, map objects, and other mission parameters.

Test Set 4				
BLUE	●	7	3	5

Figure 23: Sample Randomized Code

Scoring was based on time to recall and correctly recalled items. Time was scored as one penalty point per second to respond. Response timing began when prompted for the answer and ended when the subject stated the last item or verbalized they could not recall any more items.

3.9.2.6 Stroop Task

After completion of the randomized code recall, the test subject would turn to a test card as shown Table 5 below. The Stroop cognitive task consisted of correctly verbalizing the color of the printed word, not the color being named by the word itself. A follow-up (opposite) Stroop cognitive task was then given in which the subject verbalized the color being named by the word.   In both tests the subject would be given a number indicating from which line to begin reading and did not know which type of Stroop would be requested first. Once the number was given, the subject was scored on the time to complete all six words (Example: Line 16 words, in Table 5 below: purple blue green yellow green red) as well as accuracy of the read back. This task assessed selective attention and mental flexibility. Scoring was based on time to answer and number of correctly interpreted colors. Time was scored as one penalty point per second to respond.

Response timing began when prompted for the answer and ended when the subject stated the last item.

Table 5: Stroop Task

1	BLUE	YELLOW	RED	RED	BLUE	ORANGE
2	RED	YELLOW	BLUE	BLUE	GREEN	ORANGE
3	GREEN	YELLOW	ORANGE	YELLOW	YELLOW	PURPLE
4	BLUE	PURPLE	PURPLE	RED	GREEN	RED
5	BLUE	RED	YELLOW	PURPLE	YELLOW	PURPLE
6	YELLOW	GREEN	BLUE	RED	RED	BLUE
7	PURPLE	GREEN	PURPLE	RED	YELLOW	PURPLE
8	ORANGE	ORANGE	RED	YELLOW	RED	RED
9	PURPLE	GREEN	GREEN	PURPLE	RED	PURPLE
10	BLUE	RED	GREEN	ORANGE	BLUE	GREEN
11	BLUE	ORANGE	PURPLE	BLUE	PURPLE	RED
12	GREEN	YELLOW	YELLOW	BLUE	YELLOW	BLUE
13	RED	BLUE	YELLOW	YELLOW	BLUE	YELLOW
14	BLUE	RED	BLUE	BLUE	PURPLE	YELLOW
15	GREEN	RED	GREEN	ORANGE	PURPLE	BLUE
16	RED	GREEN	BLUE	ORANGE	PURPLE	PURPLE
17	GREEN	GREEN	YELLOW	BLUE	PURPLE	YELLOW
18	RED	BLUE	GREEN	YELLOW	YELLOW	GREEN
19	ORANGE	ORANGE	BLUE	PURPLE	ORANGE	BLUE
20	RED	RED	PURPLE	GREEN	ORANGE	RED

3.9.2.7 Operational Procedure Assessment (Ops Check)

Upon completion of the Stroop task, the test subject would perform an in-flight Operational Procedure Assessment (Ops Check) check from memory in accordance with 1F-16CM-1. Subjects did not have a copy of the checklist readily available to read. The check is shown in Table 6 below.

Table 6: F-16DM In-Flight Operational Check

1.	Fuel – Check quantity/transfer/balance
2.	FUEL QTY SEL knob - NORM
3.	Oxygen system - Check
4.	Cockpit pressurization - Check
5.	Engine instruments - Check
6.	HYD PRESS A & B - Check

The test subject read back numbers for total fuel quantity, cockpit pressure, engine RPM, and hydraulic system A/B. The TD recorded the time required for the test subject to complete the procedure and noted if any steps were omitted. This task assessed subject long-term memory recall and was operationally representative of typical operational tasks completed during flight phases.

Scoring was based on time to perform the ops check and correctly executing all steps. One penalty point was applied for each incorrect step. Time was scored as one penalty point per second to complete the checklist. Response timing began when the subject began verbalizing procedures and ended when the subject stated the last item.

3.9.2.8 Scoring Algorithm

TDs were responsible for ensuring a minimum of one-minute rest was accomplished at less than 3 G between each test set. Borg score and cognitive assessments were accomplished during this time. After the 60-second minimum rest time, the test subject was penalized 0.1 points for each second of rest in excess of the 60 second minimum. If at any point in the sortie, the TD, TC, or test subject believed that further testing was unwarranted due to excessive crew fatigue, light-loss, or physiological impairment, the crew would cease testing and return to base.

After the four test sets were accomplished, the TD tallied a score based on accuracy of the G maintained and time to complete the full set of four test sets. Scores were calculated based on risk/reward system by accuracy of G-tracking performance, offering less penalty for successfully maintaining precise G within specified tolerances, while minimizing rest time. Poor G-tracking performance yielded more penalty points against the total score; therefore, the test subject was encouraged to strategize their rest time taking into account their level of fatigue and predicted performance. In-flight augmentation through %HRR biofeedback was used by the test subject to aid in assessing PC state, decision-making (rest time), and G-tracking performance.

A basic summary of the scoring algorithm is shown below:

G-Tracking Error: 1+ (Gs (tenths) outside tolerance ± 0.2 Gs) * (time exceeded)

Time Penalty Error: 1+ (Time (in seconds) exceeding 60 sec (min rest time)) * 0.1

Test Set Error Score: G-Tracking Error * Time Penalty

Total Error Score: Test set 1 + Test set 2 + Test set 3 + Test set 4

Lower scores were an indicator of good G-tracking performance and/or less rest time. Higher scores signified degraded performance and/or longer rest times. Ideally, the weighting algorithm would have been extensively vetted from sample G-tracking errors and time penalties to ensure correct correlations were made of overall risk/reward performance. Due to testing time constraints, no prior analysis was conducted of the scoring algorithm to determine if desired characteristics were weighted appropriately.

3.10 Testing Resources

3.10.1 Modeling and Simulation

Flight profile development and pilot proficiency training was accomplished in the USAFTPS F-16 Unit Training Device (UTD). The UTD is a very basic F-16 simulator with a single color screen looking through the Heads-Up-Display (HUD). The cockpit has all the same switches, throttle, control stick, and displays as the aircraft. The UTD is a decent avionics trainer with the ability to practice specific test profiles to identify entry airspeed and altitude parameters.

Additionally, PECGU and GETAC familiarization, AFE validation, F-16 high-G qualification, practice profile exposure, and initial data collection was accomplished as a buildup in the centrifuge at BCB, Texas.

3.10.2 Test Range/Environment

Centrifuge testing was accomplished at Brooks City-Base, Texas with the gondola set to an F-16 configuration to include a 30-degree tilt back seat angle and side stick mount. All airborne testing was accomplished at Edwards AFB, CA and flown within the R-2508 complex in day Visual Meteorological Conditions (VMC).

3.10.3 Test Aircraft

The test aircraft for all flight test sorties was a DAS equipped F-16DM, tail numbers 87-0391 and 90-0797, with a 9G compatible configuration. The Automated Ground Collision Avoidance System (AGCAS) was noted as “highly desirable” by the safety review board (SRB) but not required for flight test. The F-16DM was a tandem, single engine fighter aircraft as shown in Figure 24.

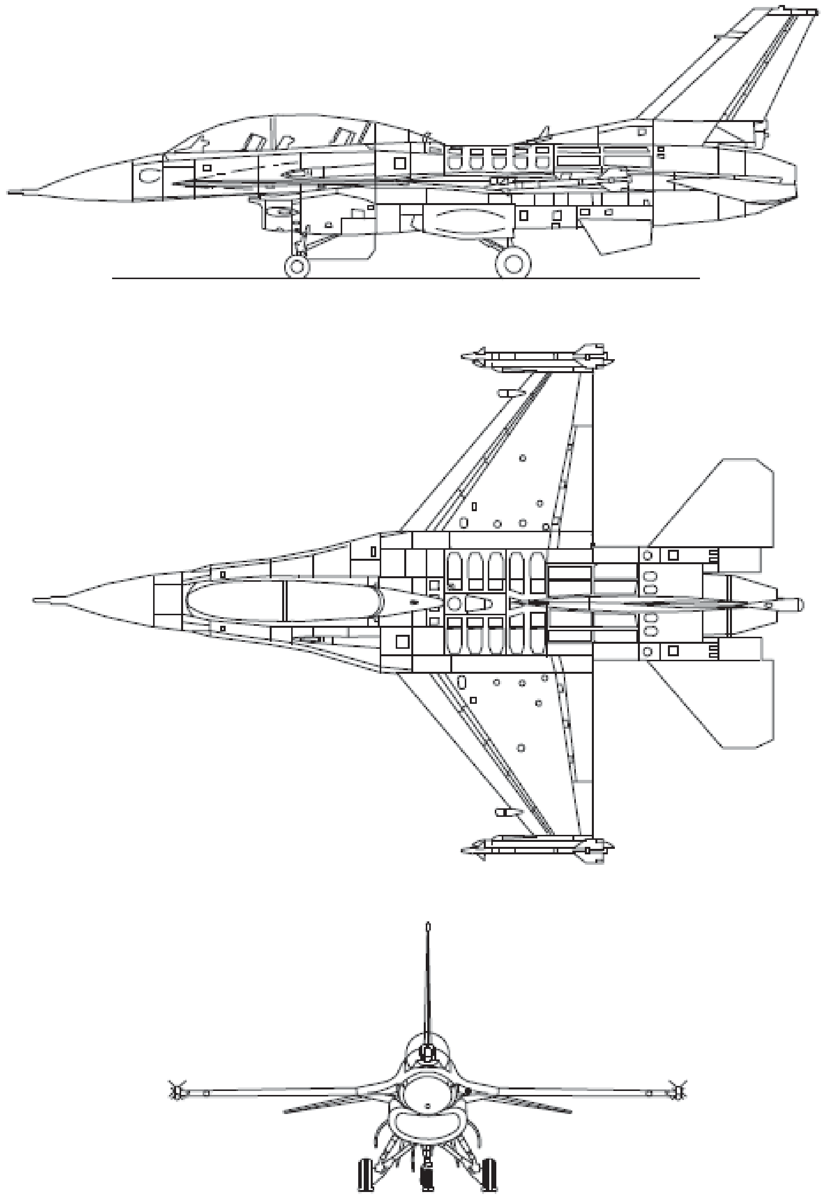

Figure 24: F-16DM 3-View

3.11 Limitations and Constraints

The combined PECGU-GETAC system lacked data recording capability to measure and save subject %HRR data to the GETAC. As a mitigating procedure, test subjects wore the Garmin with incorporated optical wrist-mounted HR sensor. The Garmin stored HR data vs. time in a graphical format. Additionally, during sorties in which biofeedback was incorporated, subjects read their current %HRR over hot microphone at the beginning and end of each cognitive assessment set for hand recorded data. This led to constraints in the test execution, as subject rest time could not be equally scored, since added tasks were necessary during sorties with biofeedback.

During Phase 3 centrifuge testing, %HRR was not available for display due to GETAC system immaturity. Instead, raw HR was displayed direct to the test subject. To compensate, the test subject would read their HR and the TC would read back the test subject resulting %HRR using a HR to %HRR conversion table specific to each test subject. Modifications were incorporated into the GETAC after Phase 3 centrifuge testing and prior to Phase 4 flight tests. The modifications resulted in a true %HRR display, as opposed to a raw HR display as previously evaluated in Phase 3.

Furthermore, during Phase 3 test subjects had direct control of a gun cross on a display (inside the centrifuge gondola) via a side mounted control stick. The displayed target performed a series of random maneuvers that manifested in lead and lag on the display. In summary, the tracking task comparison between flight test and centrifuge test were not the same task and total error score should not be directly compared.

Lastly, due to time constraints, the AMPSS 3.0 was not approved by the F-16 System Program Office (SPO) for flight testing due to incomplete windblast testing. STO 8 data were collected only from centrifuge testing.

3.12 Chapter Summary

This chapter opened with a reminder of the research question and reiteration of the motivation behind real-time biofeedback to operators of high performance aircraft. Next, a brief recap was given of the principles that unify this research which include:

human physiology, biofeedback, human-machine systems, PC sensors, workload, and human performance. Third, the STOs, MOPs, SUT and test roles and responsibilities were explained. Fourth, a thorough description emphasized all materials and equipment associated with the four phases of this research. Fifth, a T&E section highlighted the processes and procedures that supported the experimental design in a chronological format through all four phases as each applied to the research STOs. Lastly, test resources were highlighted as well as limitations and constraints that impacted test conduct and data collection. Chapter 4 expounds on the results and analysis of data collected from the methodology.

4. Results and Analysis

4.1 Chapter Overview

This chapter describes the results and analysis of the four-phased research methodology outlined in Chapter 3. Results and analysis are address in a chronological format following the specific test objectives (STOs) and measures of performance (MOPs) outlined in previous chapters and Table 7 below.

Table 7: Specific Test Objectives (STOs) and Measures of Performance (MOPs)

Phase 1 (C1)	**Initial hardware and subject centrifuge trials** **STO 1: Assess initial hardware and test profile** MOP 1: Cardiorespiratory response MOP 2: Tracking performance MOP 3: Workload Level MOP 4: Hardware accuracy
Phase 2 (L1)	**Laboratory VO_{2max} testing** **STO 2: Determine operator peak physiologic output** MOP 1: Maximal Oxygen Consumption ($VO_{2}max$)
Phase 3 (C2) ***Phase 4 (F1)***	**Training and build-up approach centrifuge testing** **Flight testing** *Combined STOs and MOPs for phases 3 and 4
	STO 3: Determine operator PC state MOP 1: Percentage Heart Rate Reserve (%HRR) MOP 2: Portable ECG Unit (PECGU) Accuracy MOP 3: Cognitive State
	STO 4: Determine the effect of providing biofeedback on operator PC state awareness MOP 1: Awareness of PC state without %HRR biofeedback MOP 2: Awareness of PC state with %HRR biofeedback
	STO 5: Determine effect of providing biofeedbaack on decision-making MOP 1: Decision-making without %HRR biofeedback MOP 2: Decision-making with %HRR biofeedback
	STO 6: Determine effect of providing biofeedback on tracking performance MOP 1: Centrifuge tracking task accuracy without biofeedback MOP 2: Centrifuge tracking task accuracy with biofeedback MOP 3: Airborne G-tracking accuracy without biofeedback MOP 4: Airborne G-tracking accuracy with biofeedback
	STO 7: Evaluate human system integration of biofeedback display into fighter cockpit MOP 1: Usability of display
	STO 8: Collect Aircrew Mounted Physiologic Sensor Suite (AMPSS 3.0) Data

4.2 Phase 1 (C1): Initial Hardware and Subject Centrifuge Trials

4.2.1 STO 1: Assess Initial Hardware and Test Profile

As highlighted in Table 7 of this chapter, the STO for Phase 1 was focused around assessing various hardware configurations for future testing and measuring subject cardio response, workload levels, and tracking performance. The centrifuge test profile in Table 3 in Chapter 3 directly supported this STO. A detailed description of the hardware used is included in Chapter 3. Table 8 below provides demographic information about the seven subjects from the High-G Acceleration Human Subject Panel (HGAHSP). All subjects were male between the ages of 22 to 33. The column labeled as baseline HR is equivalent to resting HR (HR_{rest}). The column labeled APMHR indicates age-predicted maximum HR (HR_{max}). This value is calculated by subtracting the subject's age from 220. The column labeled Zephyr indicates the exact Zephyr puck number that specific subject was wearing. The final three columns indicate different percentage heart rate reserve (%HRR) indices at 50%, 70%, and 85% HRR based on Equation 1 in Chapter 2.

Table 8: Phase 1 Test Subject Demographics

Subj #	Date of Exp.	AM/PM	Zephyr #	Age (yrs)	"Baseline" HR (bpm)	APMHR (bpm)	HRR (bpm)	50%HRR (bpm)	70%HRR (bpm)	85%HRR (bpm)
1	2-Nov	AM	1	30	76	185.3	109.3	130.6	152.5	168.9
2	2-Nov	AM	2	29	73	185.9	112.9	129.5	152.1	169.0
3	2-Nov	PM	3	30	83	185.3	102.3	134.1	154.6	169.9
4	2-Nov	PM	4	33	100	183.2	83.2	141.6	158.2	170.7
5	3-Nov	AM	5	29	84	185.9	101.9	135.0	155.4	170.6
6	3-Nov	PM	1	25	75	188.7	113.7	131.8	154.6	171.6
7	4-Nov	AM	2	22	88	190.7	102.7	139.4	159.9	175.3

4.2.1.1 MOP 1: Cardiorespiratory Response

As discussed in Chapter 3, KBRWyle Science, Technology, and Engineering Group (KBRWyle) Electrocardiogram (ECG) leads were attached to the test subject's chest to provide a "truth source" of HR data. The four primary HR sensors were: Elbit Systems Canary Pilot Health Monitoring System (Elbit), Zephyr BioHarness 3.0

(Zephyr), KBRWyle ECG, and the Portable Electrocardiogram Unit (PECGU), the primary prototype hardware-under-test (HUT). Additionally, the Aircrew Mounted Physiological Sensor Suite (AMPSS) 2.5 was tested as a potential avenue for collection an analysis of respiratory metrics. HR data were collected for Wyle, Elbit, and Zephyr on all seven subjects. PECGU data were collected for Subjects 1, 5, 6, and 7. PECGU data was corrupt for Subjects 2, 3, and 4.

A time series plot of the four primary HR sensors for Subjects 1, 5, 6, and 7 can be seen in Figure 25 below. For Subject 1 and 7 it appears the Elbit is out of phase with other sensors. The plot for Subject 5 shows that all sensors appear to follow the Wyle HR "truth data" plot. Looking only at the time series plots provides minimal analysis of the data. Further analysis is discussed in MOP 4 Hardware Accuracy of this STO.

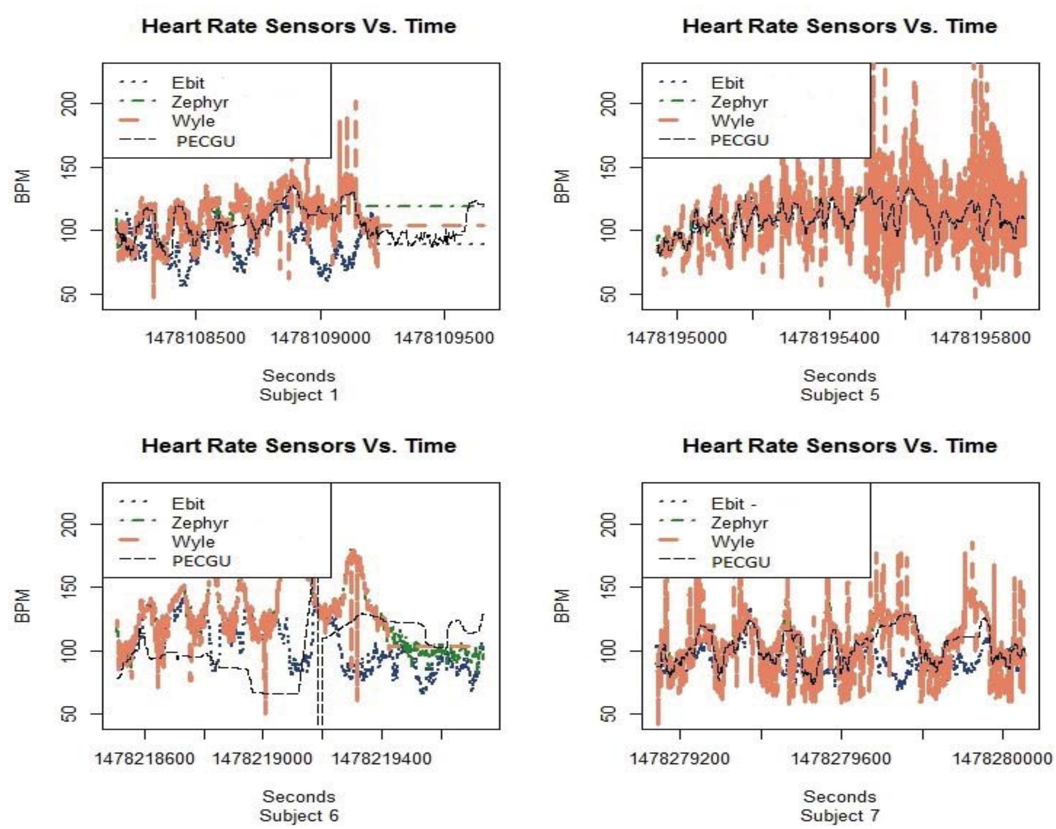

Figure 25: Phase 1 Heart Rate Sensors vs. Time

Cardio responses varied between subjects. In all cases subjects showed drops in HR during low-G points and elevated HR during high-G points. Some subjects showed greater HR recovery between high-G and low-G test points than others. Additionally, all subjects reached peak HRs during simulated air-combat-maneuvering (SACM) test points at the end of the profile which were characterized by longer durations and high peak G values. This is demonstrated in Figure 26 below, showing Subject 1. The value labeled "HR-Calculated" was taken from the best data source (Wyle) and is plotted against the Elbit HR sensor. Subject 1 demonstrates progressively increasing HR peaks commensurate with increasing high-G test points. HR recovers less and less during low-G resting points as subsequent high-G points increase in amplitude. This was a dominant trend among most subjects and is shown in the Elbit vs. Wyle plots of all Phase 1 subjects in Appendix L.

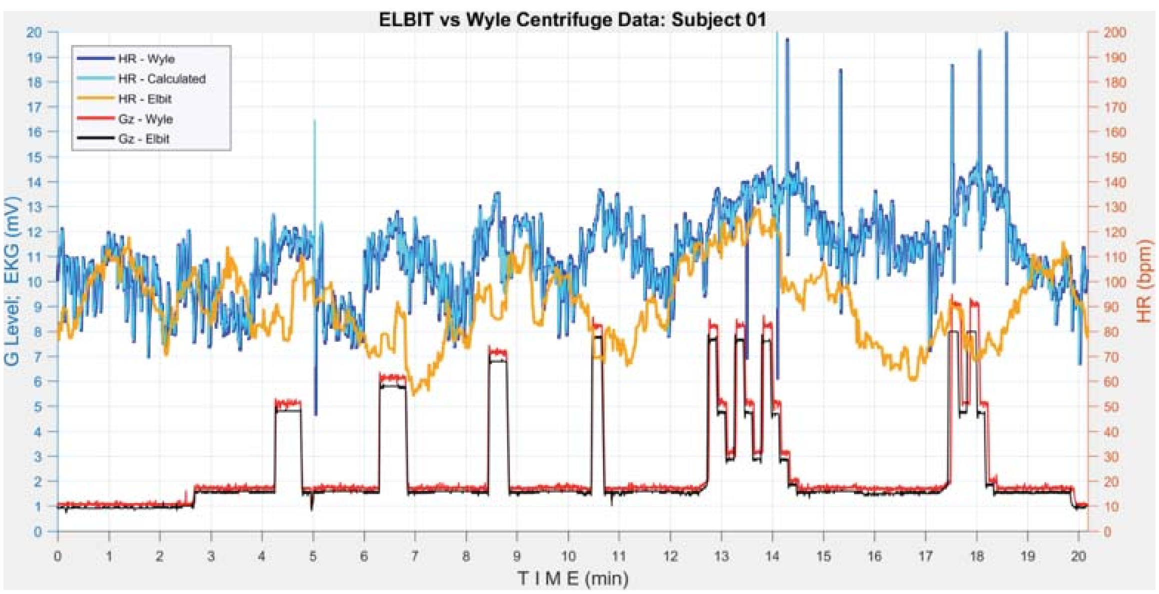

Figure 26: Subject 1 Phase 1 Elbit vs. Wyle HR Sensors

AMPSS 2.5 data was collected on all seven subjects and delivered to the 711th Human Performance Wing (711 HPW) for analysis. Continued challenges with accurate sensor measurement and collection of subject oxygen (O_2)/carbon dioxide (CO_2) pressures and mass flow rates were discovered. Based on project timeline and further scoping this research to include only cardio metrics, a decision was made to discontinue incorporation of AMPSS 2.5 in this project. As a led in to United States Air Force Test Pilot School (USAFTPS) 17A HAVE HOPE Test Management Project (TMP), this Phase 1 testing occurred in November 2016, before 17A entered TPS. Subsequently, members of USAFTPS 16B conducted follow up research in early 2017 of AMPSS 2.5 in a TMP named HAVE PUFFIN, as cited in Chapter 2. AMPSS 3.0 was later added to this research in May 2017 and the hardware was tested during Phase 3. All AMPSS 3.0 data were collected in pursuit of 711 HPW objectives.

4.2.1.2 MOP 2: Tracking Performance

Figure 27 below highlights the root mean square error (RMS error) values for tracking tasks of the seven subjects during different stages of the Phase 1 profile. Lower values indicate better tracking performance. Aside from Subject 4, all subjects had near-constant tracking performance regardless of which stage they were in the profile. Based on these the results, it was considered that subjects were potentially not being challenged enough during the profile and efforts needed to be made before Phase 3 to increase strain on the subject in an effort to find indices of performance drop.

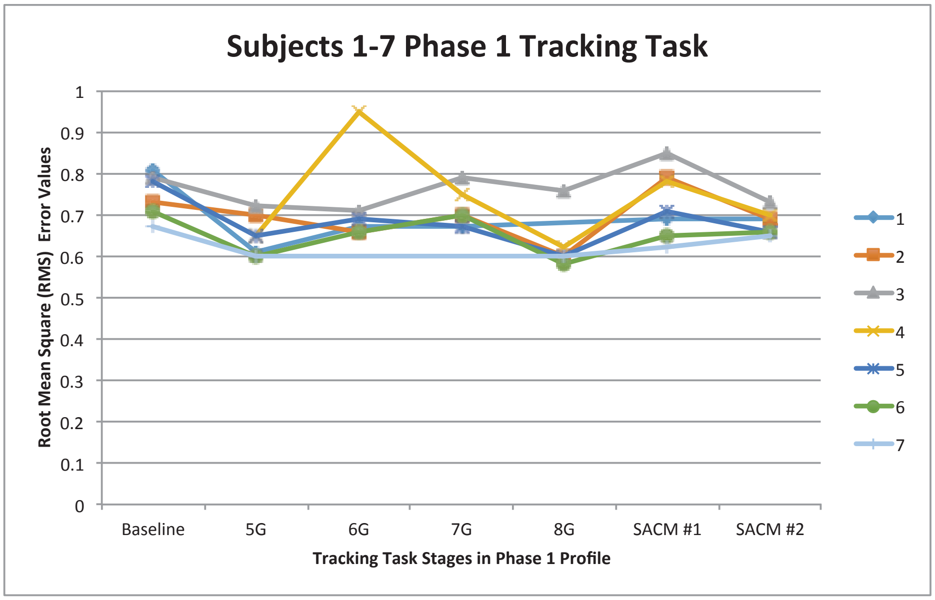

Figure 27: Subjects 1-7 Phase 1 Tracking Task RMS Error

4.2.1.3 MOP 3: Workload Level

Figure 28 below presents a summary of Bedford Workload Scale (BWS) values given by the seven subjects at different stages of the profile. BWS values are measured from 1 to 10 in accordance with the BWS discussed in Chapter 2. Looking at each subject, it is evident that 5 out of 7 subjects reported a low (and near constant) BWS value (indicating not a challenging task) over the duration of the profile.

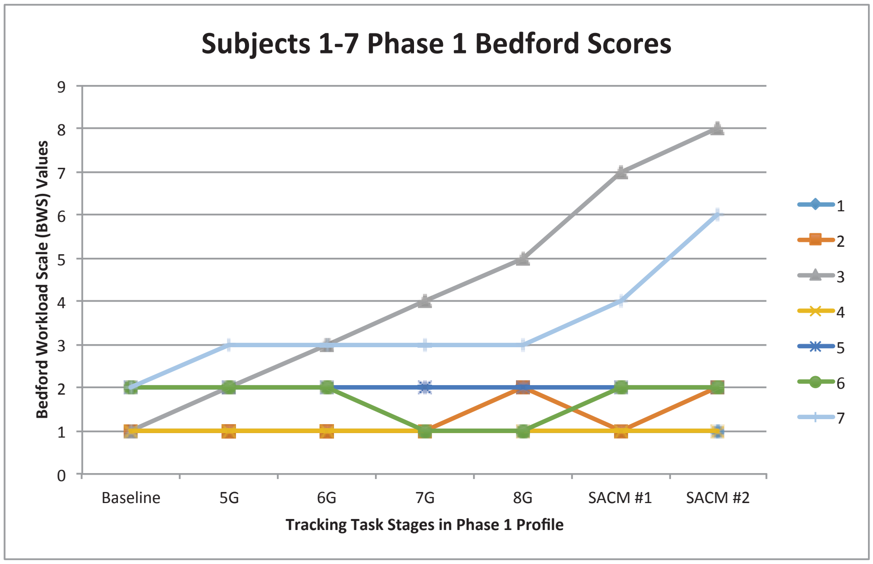

Figure 28: Subjects 1-7 Phase 1 Bedford Workload Scale (BWS) Values

Looking at physiological indicators in Table 9 below, both peripheral and central light loss is indicated in the columns labeled "Reported L/L." Both values are percentages (0-100%) with peripheral light loss values listed first and central light loss values listed second. Only 2 of 7 subjects reported any form of central light loss during the profile, with one instance (Subject 1) only occurring after the final high-G test point. All subjects did report some form of peripheral light loss during the profile. Furthermore, all seven subjects reported not having significant issues with G tolerance or duration of the profile.

Table 9: Phase 1 Tracking Task Performance and Workload

Subj #	Tracking Task (RMS error)	Bedford Wrkld Rating	5G/30 Reported L/L	TT	Bed	6G/30 Reported L/L	TT	Bed	7G/20 Reported L/L	TT	Bed	8G/10 Reported L/L	TT	Bed	SACM1 Reported L/L	TT	Bed	SACM2 Reported L/L	Tracking Task	Bed
1	0.81	1	0/0	0.61	1	5/0	0.67	1	10/0	0.67	1	10/0	/	1	0/0	0.69	1	40/20	0.69	1
2	0.73	1	0/0	0.7	1	0/0	0.66	1	0/0	0.7	1	0/0	0.6	2	50/0	0.79	1	50/0	0.69	2
3	0.79	1	0/0	0.72	2	0/0	0.71	3	0/0	0.79	4	100/70	0.76	5	100/90	0.85	7	100/90	0.73	8
4	/	1	0/0	0.65	1	0/0	0.95	1	5/0	0.75	1	0/0	0.62	1	0/0	0.78	1	10/0	0.7	1
5	0.78	2	0/0	0.65	2	0/0	0.69	2	0/0	0.67	2	0/0	0.6	2	0/0	0.71	2	40/0	0.66	2
6	0.71	2	15/0	0.6	2	0/0	0.66	2	0/0	0.7	1	15/0	0.58	1	0/0	0.65	2	40/0	0.66	2
7	0.67	2	0/0	0.6	3	0/0	/	3	0/0	/	3	0/0	0.6	3	20/0	0.62	4	10/0	0.65	6

Based on the results of MOPs 2 and 3 it was identified that improvements were necessary to increase the level of difficulty of the subject profile before Phase 3 centrifuge tests. First, the recovery time allowed for subjects between high-G test points could be decreased. Shortening this time from 60 seconds to 30 seconds would allow less time for the subject's cardiovascular system to recover, thus increasing physical exertion. Second, an increase in total profile duration may eventually trigger more subject fatigue and a performance drop. This option is less efficient and costs more money. Third, increasing the amplitude and duration of high-G points (more area under the curve) would potentially initiate subject fatigue sooner. Lastly, enabling the subjects to execute the tracking task while under G and giving them direct control of the centrifuge gondola G would force subjects to fight through high-G forces while attempting to execute an extremely tight closed-loop-control tracking task. This setting would be much more representative of actual airborne execution and an operational environment as the subject is never "relieved of control". Ultimately, a combination of tracking while under high G and pulling more G in less time (more area under the curve) was identified as the best option to pursue moving towards Phase 3.

Further discussion was continued with the KBRWyle team in the months between Phase 1 and Phase 3 testing. Allowing subjects direct control of gondola G presented some programming challenges and was not feasible. However, with some added work required, successful modifications were made to the centrifuge configuration to allow tracking while under G.

4.2.1.4 MOP 4: Hardware Accuracy

As discussed in MOP1 of this STO, HR data were collected for Wyle, Elbit, and Zephyr on all seven subjects. PECGU data were collected for Subjects 1, 5, 6, and 7. A time series plot of the four primary HR sensors for Subjects 1, 5, 6, and 7 can be seen in Figure 25. In order to provide further data analysis, a normalized cross-correlation function (NCCF) was performed on the time series plots for the four primary HR sensors. Results of the NCCF are presented in Table 10 below.

Table 10: Normalized Cross-Correlation Function of Heart Rate Sensors

		Sensor			
Sensor	**Subject**	Elbit	Zephyr	Wyle	PECGU
Elbit	1	--	0.0847	0.0872	0.0518
Zephyr	1	--	--	0.5594	0.4228
Wyle	1	--	--	--	0.7137
PECGU	1	--	--	--	--
Elbit	5	--	0.7704	0.7091	0.7568
Zephyr	5	--	--	0.8225	0.9048
Wyle	5	--	--	--	0.7539
PECGU	5	--	--	--	--
Elbit	6	--	0.1454	0.0899	-0.3693
Zephyr	6	--	--	0.9777	-0.1737
Wyle	6	--	--	--	-0.1425
PECGU	6	--	--	--	--
Elbit	7	--	0.1635	0.0916	0.149
Zephyr	7	--	--	0.8901	0.8124
Wyle	7	--	--	--	0.7742
PECGU	7	--	--	--	--

LEGEND	
Green	> 0.7
Yellow	0.4 – 0.7
Red	< 0.4

An ordinary correlation function is a measure of the statistical correlation between two random variables and is a tool often used in signals analysis and processing as a measure of the similarity between two signals. An auto correlation is a measure of the correlation of a signal with itself. A cross-correlation function (CCF) is a measure of the similarity of multiple series as a function of the displacement of one relative to the others and takes into account the autocorrelation between observations of the same variable in a time series. Finally, the correlation data is normalized through a NCCF, which contains values between -1 and 1. A value of 1 indicates that at a specific time alignment (t), the two times series have perfect alignment and the exact same shape. A value of -1 indicates the two series have the exact same shape, but opposite sign, or 180 degrees out-of-phase. A value of 0 shows the two series are completely uncorrelated. After applying a NCCF, correlation coefficients greater than 0.7 indicates a good match (Wackerly, Mendenhall, & Scheaffer, 2008).

Based on the results in Table 10, and maintaining our Wyle sensor as a truth source, several assessments were made. The Zephyr was accurate on 3 of 4 subjects with correlation coefficients greater than 0.82, and showed fair correlation in Subject 1 with a coefficient of 0.56. The PECGU was accurate on 3 of 4 subjects with correlation coefficients greater than 0.71, and showed poor correlation in Subject 6 with a coefficient of -0.14. The Elbit was inaccurate on 3 of 4 subjects with correlation coefficients less than 0.1, but showed good correlation in Subject 5 with a coefficient of 0.71.

In summary, both the Zephyr and PECGU were usually in agreement with Wyle. The Elbit was usually not in agreement with the other sensors. Additionally, Figure 29 further demonstrates the Elbit sensor often being 180 degrees out-of-phase with Wyle "truth source" during high-G test points, but not at low-G test points. Hence, the Elbit sensor exhibited an inaccuracy while under G.

Based on these results from Phase 1, the PECGU hardware prototype was deemed valid to progress as the primary HR sensor for Phases 2, 3 and 4. As an already mature system, Zephyr was no longer necessary moving forward. Based on the limitations discussed, the Elbit was no longer used in Phases 2, 3, and 4.

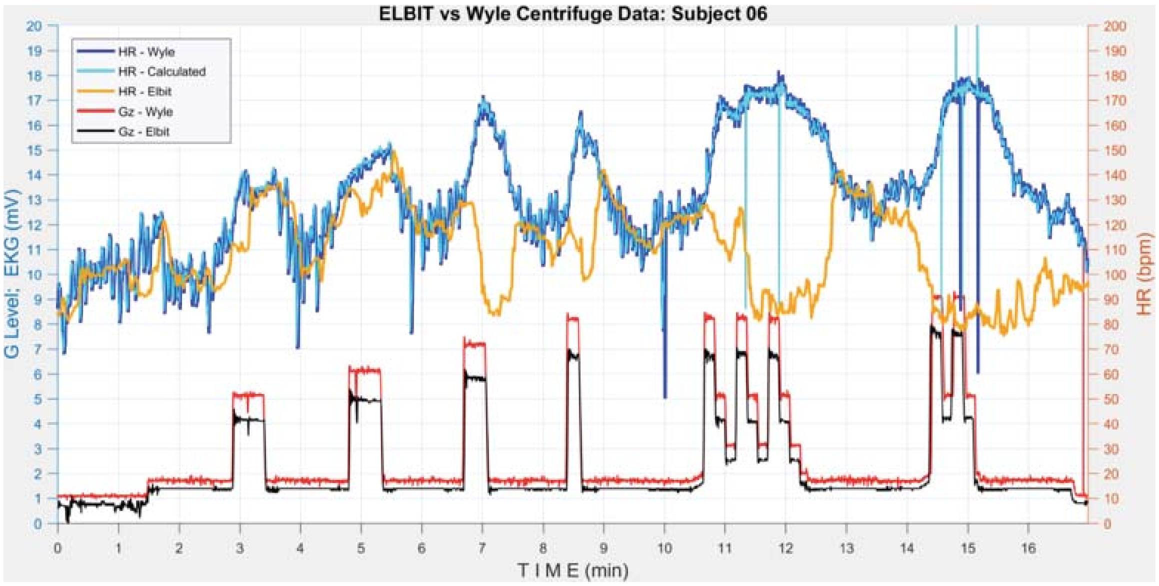

Figure 29: Phase 1 Subject 6 Elbit vs. Wyle HR Sensors

4.3 Phase 2 (L1): Laboratory VO_{2max} Testing

As highlighted in Table 7 of this chapter, the STO for Phase 2 was to determine a baseline operator maximal oxygen consumption rate (VO_{2max}), peak physiologic output, and corresponding exercise-induced HR_{max} for each subject.

4.3.1 STO 2: Determine Operator Peak Physiologic Output

This STO was designed to enable the test team to measure a baseline peak physiologic output for each test subject. Since biofeedback is based on specific test subject personal physiological limits, VO_{2max} data were used to develop a subject-customized %HRR scale used during subsequent phases and STOs of this research.

4.3.1.1 MOP 1: Maximal Oxygen Consumption (VO_{2max})

This MOP measured VO_{2max} and HR_{rest} values in order to develop minimum and maximum HR values for each of the test subjects needed for %HRR biofeedback. Measuring an individual's VO_{2max} allows a more accurate and reliable exertion-based HR_{max}.

Table 11 below shows a summary of subject demographics and VO_{2max} results. This table also includes the Borg Rating of Perceived Exertion (RPE) score each test subject assessed at each 2-minute test increment (with corresponding HR / %HRR value) during the test. Additionally, Appendix C contains VO_{2max} graphs with oxygen consumption rate (VO_2) and HR plotted over time for all five subjects. All subjects were within 10 beats per minute (BPM) of their calculated age-predicted (220 – age) $HR_{max.}$ Furthermore, all subjects terminated based on a plateau in VO_2 despite an increase in workload, with the exception of Subject D who terminated based on a Borg RPE score of 9.

Table 11: Subjects A-E Demographics and VO_{2max} Results

Subject A	Subject B	Subject C	Subject D	Subject E
Male Age 32 Sleep: 8 hrs avg Exercise: 45-60 mins a day moderate physical activities with children Hydration: Moderate daily Other: Feels like good physical condition, mixed meals 3 times a day. 3-5 cups of coffee daily.	Male Age 29 Sleep: 6 hrs avg Exercise: 3-4 days/wk cardio & weight training Hydration: Excellent daily Other: Feels like excellent physical condition, healthy well rounded meals 3 times a day. Protein/caffein workout supplements.	Male Age 34 Sleep: 6-7 hrs avg Exercise: 3-4 days/wk cardio Hydration: Moderate daily Other: Feels like excellent physical condition, healthy well rounded meals 3 times a day. 1 cup of coffee daily.	Male Age 31 Sleep: 7 hrs avg Exercise: 2-3 days/wk cardio & weight training Hydration: Excellent daily Other: Feels like excellent physical condition, healthy well rounded meals 3 times a day. 2-3 cups of coffee daily.	Male Age 30 Sleep: 8 hrs avg Exercise: 2-3 days/wk cardio & weight training Hydration: Excellent daily Other: Feels like excellent physical condition, healthy well rounded meals 3 times a day. 2-3 cups of coffee daily.

VO2Max Results			VO2Max Results			VO2Max Results			VO2Max Results			VO2Max Results		
Min HR	64		Min HR	52		Min HR	52		Min HR	61		Min HR	50	
Max HR	197		Max HR	199		Max HR	195		Max HR	187		Max HR	198	
HR	HRR	Borg	HR	HRR	Borg	HR	HRR	Borg	HR	HRR	Borg	HR	HRR	Borg
102	28.57%	0	85	22.45%	0	97	31.47%	0	93	25.40%	0	69	12.84%	0
184	90.23%	4	177	85.03%	2	163	77.62%	3	163	80.95%	4	188	93.24%	3
191	95.49%	6	184	89.80%	3	173	84.62%	4	173	88.89%	5	191	95.27%	5
197	100.00%	7	188	92.52%	4	179	88.81%	4	184	97.62%	8	196	98.65%	7
Termination: VO2 Plateau			199	100.00%	7	185	93.01%	5	185	98.41%	9	198	100.00%	8
			Termination: VO2 Plateau			189	95.80%	7	187	100.00%	9	Termination: VO2 Plateau		
						195	100.00%	8	Termination based on Borg 9					
						Termination: VO2 Plateau								

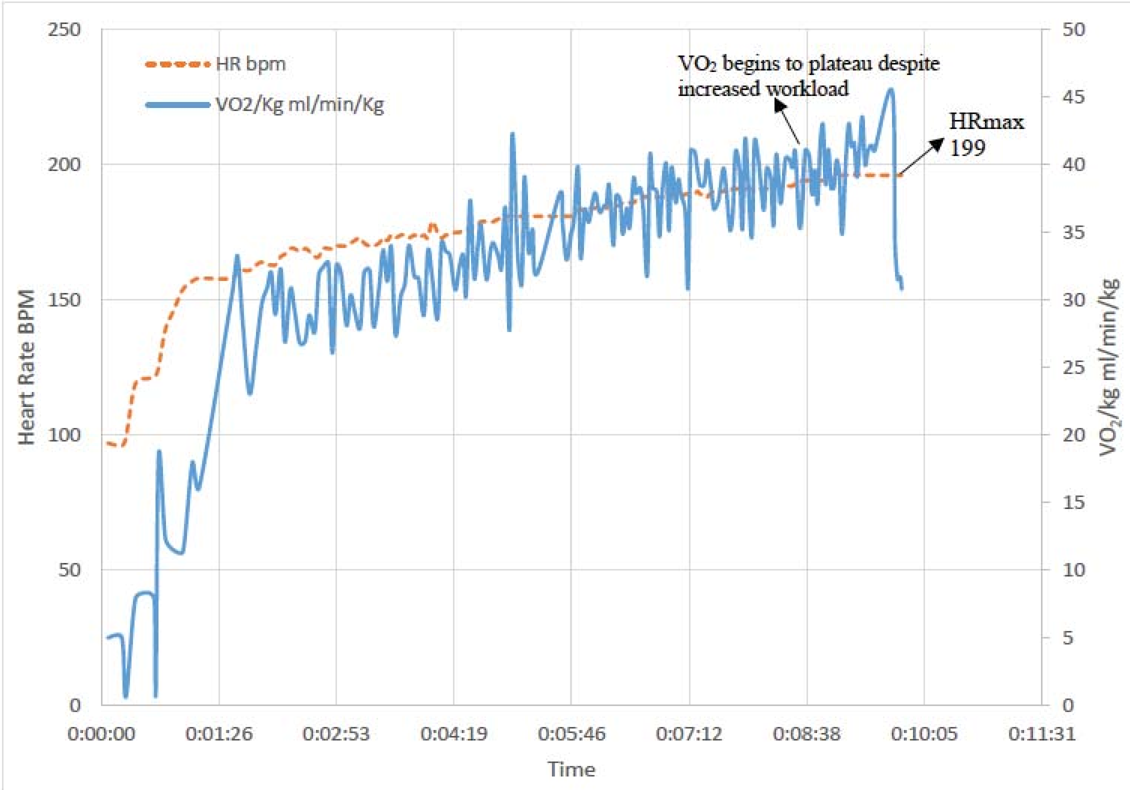

Figure 30: Subject B VO_{2max} Results

Figure 30 above shows an example of Subject B's VO_{2max} results. It is evident in the data that the HR value for Subject B had plateaued. Subject B's age-predicted HR_{max} value was 191 BPM.

In summary, HR_{rest} and HR_{max} values were accurately captured for Subjects A through E. Based on these Phase 2 results, the necessary data were attained to develop subject-specific %HRR scales for incorporation into Phases 3 and 4.

4.4 Phase 3 (C2) and Phase 4 (F1): Centrifuge and Flight Testing

4.4.1 STO 3: Determine Operator PC State

As highlighted in Table 7 of this chapter, STO 3 aimed to determine operator PC state through developing %HRR scales, measuring accuracy of the PECGU, and assessing cognitive evaluations. Each subject conducted baseline cognitive assessments in addition to HR measurements and cognitive evaluations during centrifuge and flight test. Since biofeedback is based on specific test subject personal physiological limits, Phase 2 data were incorporated into a subject-customized %HRR biofeedback scale. Accuracy of the PECGU and %HRR scale was validated in Phase 3.

4.4.1.1 MOP 1: Percentage Heart Rate Reserve (%HRR)

Percentage Heart Rate Reserve, %HRR, varied with test subject and test event (due to G-loading). Figure 31 below shows an example of HR data gathered from the KBRWyle ECG in the centrifuge, and the Garmin Fenix 3 Sapphire HR Monitor Watch (Garmin) over time with G-loading labeled as Nz. As can be seen by Subject B, %HRR tended to increase following test sets with a rapid increase in HR and subsequently tended to recover in the same amount of time. Across subjects, the amount of %HRR rise and decline varied. Some subjects showed an increased %HRR with corresponding recovery like Subject B after each test set. Other subjects showed variability in data and developed an overall trending increase in %HRR that remained at an elevated state throughout the remaining test sets. Appendix E shows %HRR derived from the KBRWyle HR data source for subjects in Phase 3 tests. Overall, data quality was good and %HRR was successfully measured for each subject.

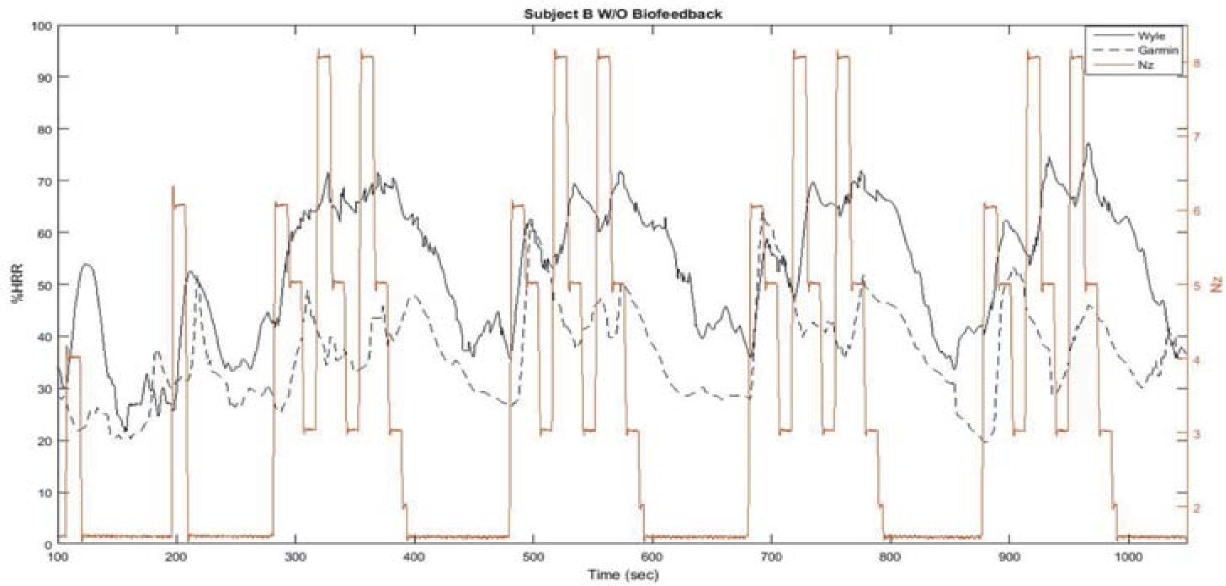

Figure 31: Subject B Phase 3 Without Biofeedback %HRR and G vs. Time

4.4.1.2 MOP 2: Portable Electrocardiogram Unit (PECGU) Accuracy

All subject HR data can be found in Appendix B, under the HR Wyle, HR Watch (Garmin), and HR PECGU columns, displaying values in terms of %HRR. HR was recorded and %HRR was derived. Table 12 below shows the statistical results of comparing the Garmin and PECGU data to KBRWyle truth data. The PECGU data was not proven to have a statistically significant difference from KBRWyle data and is assessed to be a valid source of %HRR for real-time biofeedback. Data from the Garmin, however, was proven to be different than the KBRWyle HR truth source data. The PECGU and Garmin were also proven to be statistically different measurements.

Table 12: PECGU and Garmin HR Data Accuracy

Response	2-Sample, Two tail, T-Test (Degrees of Freedom, P-Value)	Result
PECGU Accuracy versus Wyle	DF = 29, P-Value = .6	No difference between PECGU and Wyle data was proven.
Watch Accuracy versus Wyle	DF = 39, P-Value = .0083	There is a statistically significant difference between Garmin Watch and Wyle data sources.

The Garmin followed the same general rise and decline trends as the PECGU and KBRWyle data as shown previously in Figure 31 above. Garmin raw data goes through a smoothing algorithm before real-time display. Data such as awareness, decision-making, and performance were all based on PECGU %HRR and were not affected by the difference in data from the Garmin.

4.4.1.3 MOP 3: Cognitive State

Cognitive results per %HRR for all subjects can be seen in Appendix D with one example provided below in Figure 32. Cognitive results overall did not show variance with %HRR values. Completion time was the primary metric for the Stroop task and Operational Procedure Assessment (Ops check) evaluation. Stroop and Ops check values were not graphed because scores were nearly 100% accurate. As can be seen in Figure 32 below and in all subjects (Appendix D), task-specific memory recall times did not tend to vary with changes in %HRR. Code recall shows more instances of reduced accuracy at higher %HRR values for all but one subject.

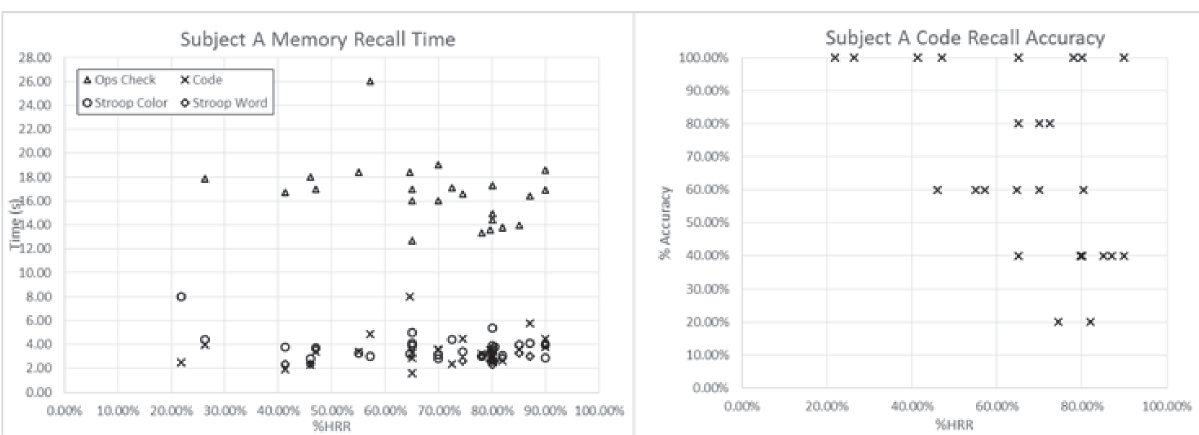

Figure 32: Subject A Cognitive Assessment Results

A Two-tailed T-test was performed to test for difference in means between tests of with biofeedback and without biofeedback. It was determined there was no statistically significant difference between cognitive response times and accuracy. Furthermore, tests showed little variance as a function of %HRR as seen in Figure 32 above and Appendix D for all subjects.

4.4.2 STO 4: Determine Effect of Biofeedback on Operator PC State Awareness

As highlighted in Table 7 of this chapter, STO 4 aimed to determine the effect of providing biofeedback on operator PC state awareness by comparing tests between without biofeedback and with biofeedback. Each subject identified a Borg RPE score at the termination of each test set both on tests conducted with and without biofeedback. Results were compared to assess if biofeedback provided added situation awareness (SA) of current PC state.

Of note, when biofeedback was available, test subjects were directed to view the GETAC display and state %HRR value before stating their Borg RPE score. This directed action aimed to determine any correlated effects of an objective %HRR value on subjective RPE scores.

4.4.2.1 MOPs 1 and 2: Awareness of PC State Without and With Biofeedback

A complete breakdown of cognitive data and Borg RPE scores versus %HRR data for each test subject can be found in Appendix D. The primary discriminator between the sets was the utilization of biofeedback to inform the test subjects of current %HRR. Statistical analysis of data associated with cognitive tests, Borg RPE scores, and current %HRR was performed by the 412th Test Wing, 812th Test Support Squadron and can be viewed in Appendix M.

When comparing Borg RPE scores between biofeedback awareness states, the histograms in Figure 33 below, indicates that Borg RPE scores were slightly higher without biofeedback as compared to scores with biofeedback. The median Borg score, as indicated by the blue line for with biofeedback was 1.97 while the median Borg score for without biofeedback was 2.89. Despite these different values, a non-parametric median test between two samples proves that this difference is not statistically significant (Kruskal Wallis Chi-square p-value =0.2522). Additionally, a parametric T-test result also proves a non-significant average difference between with and without biofeedback (Welch T p-value=0.2137).

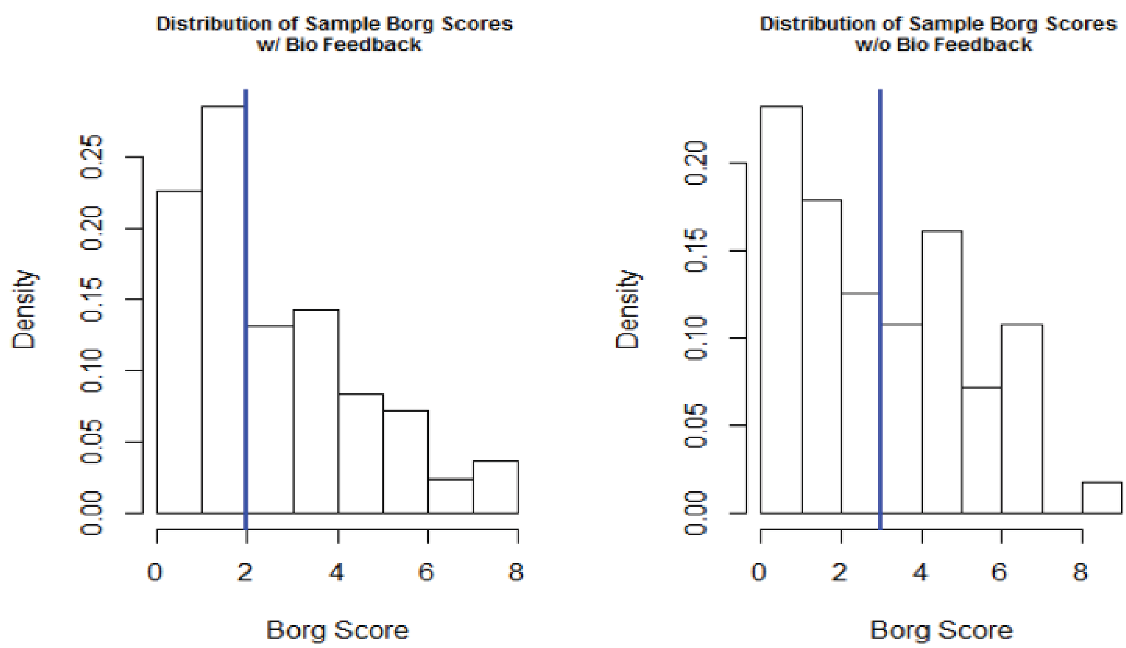

Figure 33: Borg RPE Scores With and Without Biofeedback

Centrifuge results for Borg RPE scores were on average higher across all test subjects than flights. All subjects noted that despite the G-loading and flight test technique (FTT) being identical between Phase 3 centrifuge test and Phase 4 flight test, the perceived exertion and overall discomfort was notably increased during Phase 3. As supported in Figure 34 below of Subject A, Borg RPE scores never exceeded a value of 5 during Phase 4, while reaching as high as 7 during Phase 3. However, Subject A %HRR values were higher during Phase 4.

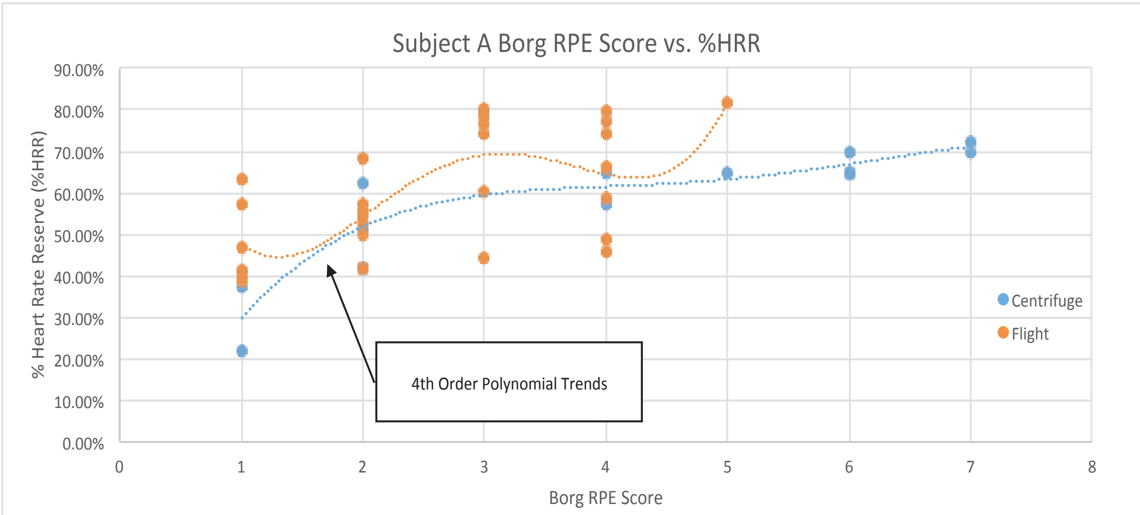

Figure 34: Subject A Borg RPE Score vs. %HRR

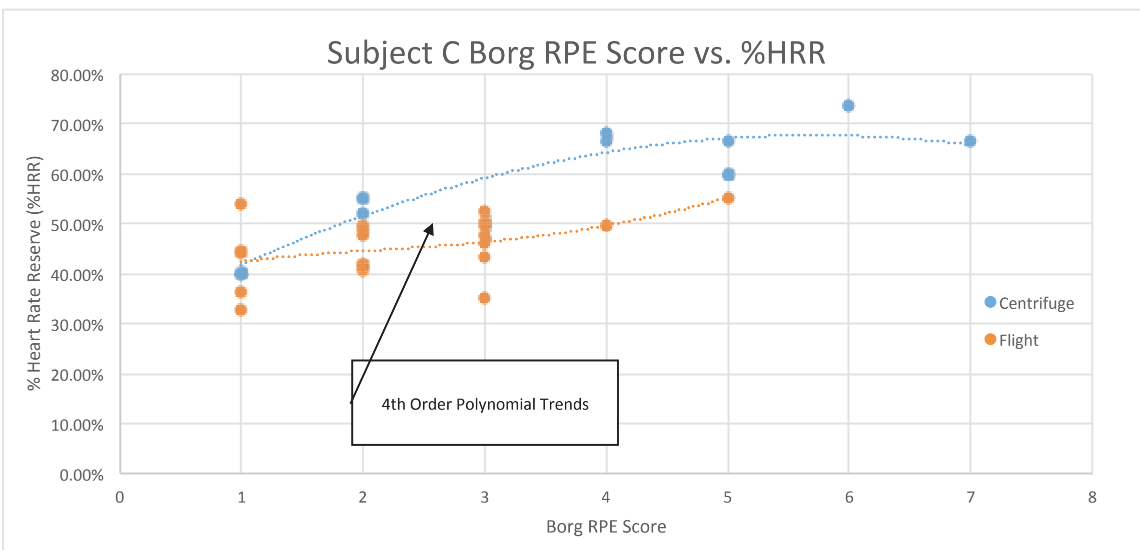

Figure 35: Subject C Borg RPE Score vs. %HRR

When compared to Figure 35 above for Subject C, Borg RPE scores also did not exceed a value of 5 during Phase 3 and reached as high as a value of 7 during Phase 4. However, counter to Subject A, Subject C experienced higher %HRR values during

Phase 3 centrifuge testing. This result supports that variability exists between subjects and each subject had different results that can only be compared to individual baseline values.

When looking at the combined results from all subjects in Appendix D, it can be seen that over the course of four test sets, Borg RPE score values tend to increase as %HRR increases. However, this increase was not statistically significant enough to draw an exact correlation between %HRR and subject perceived exertion.

As noted in Chapter 2, the Borg RPE scale was developed to be a “domain-specific” rating metric aimed towards capturing physiological strain only. However, coupled effects can occur in tests involving any form of cognitive workload (dependent on subject environment and task), and yield Borg RPE scores that fail to capture solely physiological strain.

During Phases 3 and 4, test subject Borg RPE scores differed during testing in ways unique to scores identified during VO_{2max} testing at corresponding %HRR values. While Borg RPE scores in the VO_{2max} test were primarily due to the physical exertion of the running treadmill test with minimal cognitive demand, other factors in the centrifuge and flight increased this perceived exertion at lower %HRR values. Subjects noted that when their mental workload increased in Phase 4, such as coordinating airspace, communications, establishing test set parameters and the combined functions of piloting a high performance aircraft; their Borg RPE scores may have been influenced.

4.4.3 STO 5: Determine Effect of Biofeedback on Decision-Making

As highlighted in Table 7 of this chapter, STO 5 aimed to determine the effect of providing biofeedback on operator decision-making. At the termination of each test set, each test subject was required to rest at 3 G or less for a minimum of 60 seconds while performing cognitive assessments. Upon completion of cognitive assessments, subjects were permitted to continue rest as long as deemed necessary prior to continuing to the next test set. Results were compared to assess if biofeedback provided added SA to aid in decision-making of total elected rest time.

4.4.3.1 MOPs 1 and 2: Decision-Making Without and With Biofeedback

Statistical analysis of data was performed by the 812th Test Support Squadron at Edwards AFB, CA and can be viewed in Appendix M. When comparing the overall rest time penalty error for each run, there was not a statistically significant difference between runs without versus with biofeedback. When looking at test scores, scores trended towards being slightly better (lower/less penalty time) without biofeedback, but not to a statistically significant difference. Total penalty error scores were analyzed via an analysis of variance (ANOVA) test, and it was determined that statistical differences were due to test conduct and unique test subject traits. Although total penalty error scores trended slightly higher with biofeedback, differences cannot be attributed to the presence of the biofeedback display alone.

Figure 36 below shows the compiled rest times for test subjects with respect to %HRR, both with and without biofeedback. There is a single outlier point indicating a long rest time on the plot for Subject A. This point was the result of an inflight emergency procedure, which resulted in termination of the remainder of that test set. An interesting observation was that although there was no statistical significance between rest times without versus with biofeedback, as %HRR increased rest time trended to decrease in 3 out of 4 subjects displayed below. This could be attributed to body functions, such as adrenaline and stress, aiding performance. Additional charts supporting subject cognitive results for all subjects can be found in Appendix D.

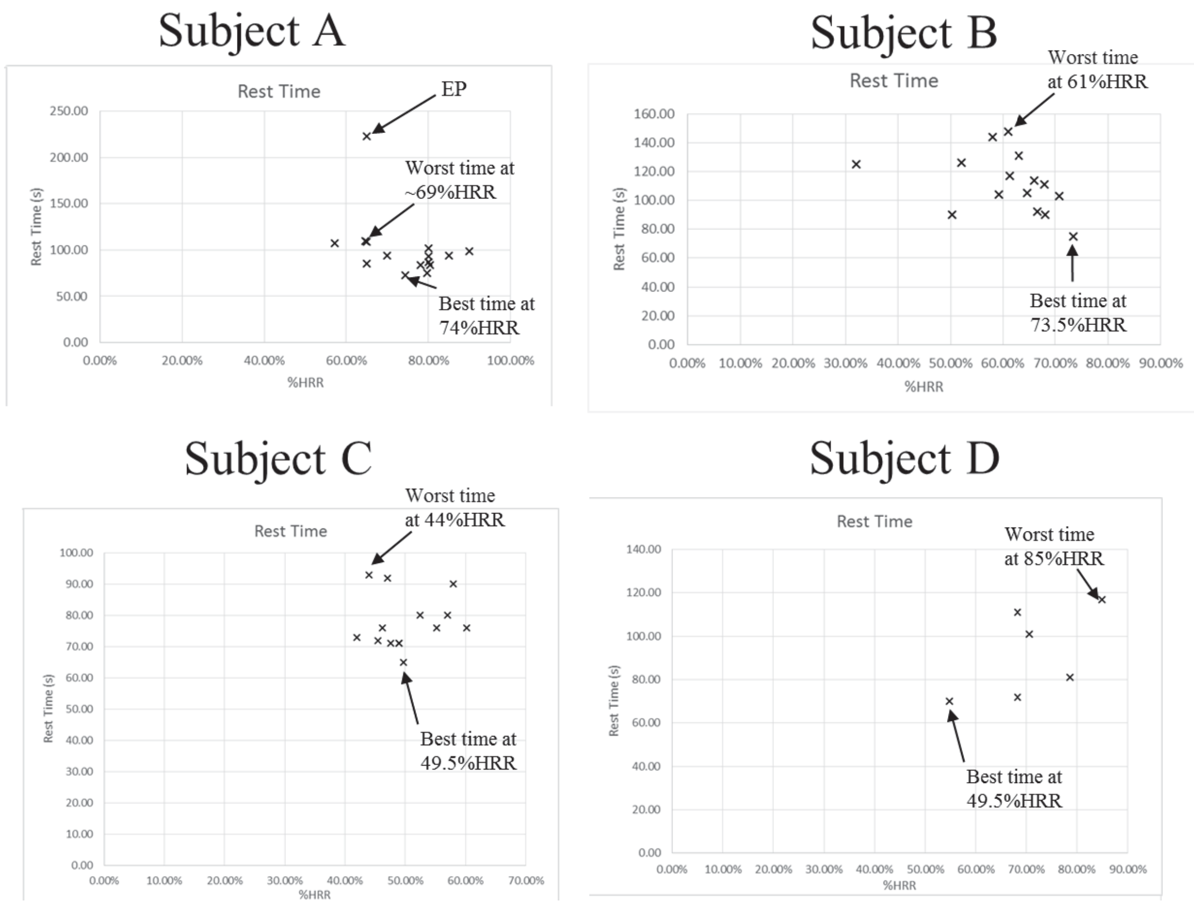

Figure 36: Rest Time Comparison for All Events

Of note, during with biofeedback tests, subjects were required to perform key additional steps between high-G test sets that were not required during without biofeedback test sets. As seen in Figure 22 in the Phase 4 test and evaluation (T&E) section, step 1 after completion of the last high-G test point of a test set, subjects had to read off their %HRR value on the PECGU and their HR value on the Garmin. Furthermore, subjects performed this step again at the end of the cognitive evaluation to aid in determining if they were ready to terminate the rest period and to continue with the next high-G test set. These additional steps resulted in "added" rest time and thus a penalty to overall score. Lower rest times and better scores during without biofeedback tests may be attributed to this aspect of test conduct and not specifically lack of biofeedback augmentation.

4.4.4 STO 6: Determine Effect of Biofeedback on Tracking Performance

As highlighted in Table 7 of this chapter, STO 6 aimed to determine the effect of providing biofeedback on operator ability to track G during a scripted test set. Data were collected during both centrifuge and flight tests. The results of with biofeedback tests were compared with the results of without biofeedback tests for each condition. The tracking task in the centrifuge was slightly different than airborne tracking as highlighted in the Limitations and Constraints section of Chapter 3.

4.4.4.1 MOPs 1 and 2: Centrifuge G-Tracking Without and With Biofeedback

A summary of all test subject centrifuge G-tracking plots can be found in Appendix F. Figure 37 below is one sample G-tracking plot of Subject B. Target location data and commanded stick position data are shown with both and upper and lower tolerance displayed in accordance with the G-tracking error formula detailed in the Scoring Algorithm section in Chapter 3.

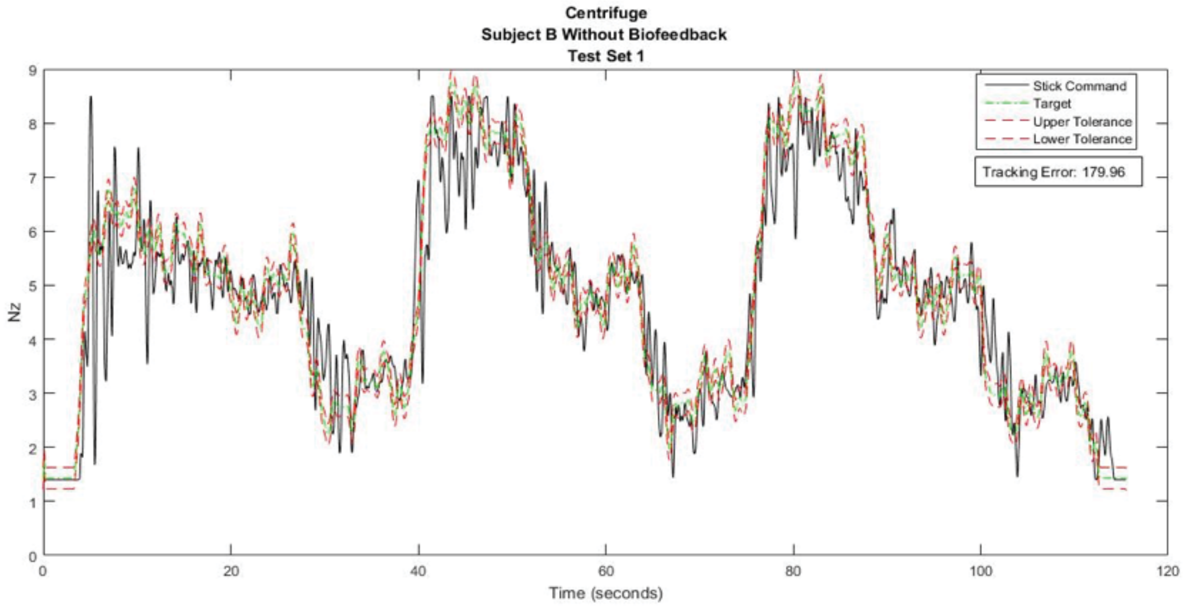

Figure 37: Phase 3 Subject B Centrifuge G-Tracking Error Without Biofeedback

Statistical results of all subjects are displayed in Table 13 below. For this statistical test, the null hypothesis states there is no statistical difference between centrifuge G-tracking scores when biofeedback was added. Data was lost for Subject A's with biofeedback test. In analyzing the P-values listed below, it can be surmised that with P-values greater than 0.05, Subjects C through E G-tracking scores do not show statistical differences and it can be stated there was a failure to reject the null hypothesis. Restated, Subjects C through E did not show statistically significant improvement between centrifuge G-tracking errors when biofeedback was added. Looking at Subject B's centrifuge G-tracking score, with a P-value less than 0.05 the null hypothesis was rejected and a statistical difference was noted. Restated, Subject B showed a statistically significant improvement when %HRR biofeedback was provided in the centrifuge.

Figure 38 below tabulates all the total centrifuge G-tracking error scores (y-axis) for Subjects A though E (x-axis). Each column represents the total G-tracking error value (by subject) and is further broken down into G-tracking error per test set on a given with biofeedback or without biofeedback flight. As seen in Figure 38 below, the primary variances in G-tracking performance were attributed to individual subjects, and could not be definitively linked to the presence of biofeedback.

Table 13: Phase 3 G-Tracking Error T-Test Without vs. With Biofeedback

T-Test P Values	
Subject A	Data Lost
Subject B	0.03
Subject C	0.19
Subject D	0.45
Subject E	0.30

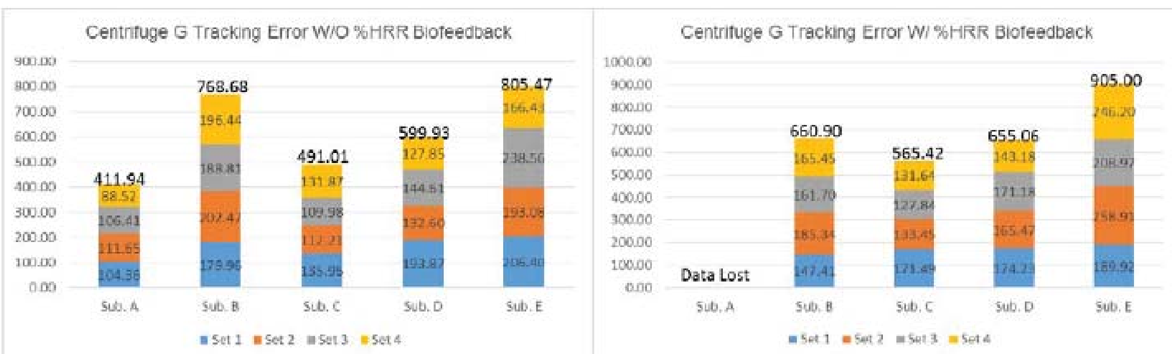

Figure 38: Subject A - E Phase 3 G-Tracking Total Error Scores

Counterbalance techniques were employed, as some subject's first test was without biofeedback while others conducted their first test with biofeedback. Test subject comments noted that learning effect of the task could have led to decreased task difficulty in subsequent tests. This may have been a greater contributing factor than the presence of biofeedback on Subject B's results. The condition in which significant improvement was shown was on the second of two centrifuge tests. Subjects were unable to practice the task before testing began; the first set was the first time they were ever exposed to the task.

4.4.4.2 MOPs 3 and 4: Airborne G-Tracking Without and With Biofeedback

A summary of all test subject Phase 4 G-tracking plots can be found in Appendix H. Flight order was randomized to counterbalance results. Some subjects performed their first flight with biofeedback and some subjects performed their first flight without biofeedback. Aircraft G was recorded and unfiltered data were processed with MATLAB.

Figure 39 below is one sample airborne G-tracking plot of Subject C. Target location data and commanded stick position data are shown with both and upper and lower tolerance displayed in accordance with the G-tracking error formula detailed in the Scoring Algorithm section in Chapter 3.

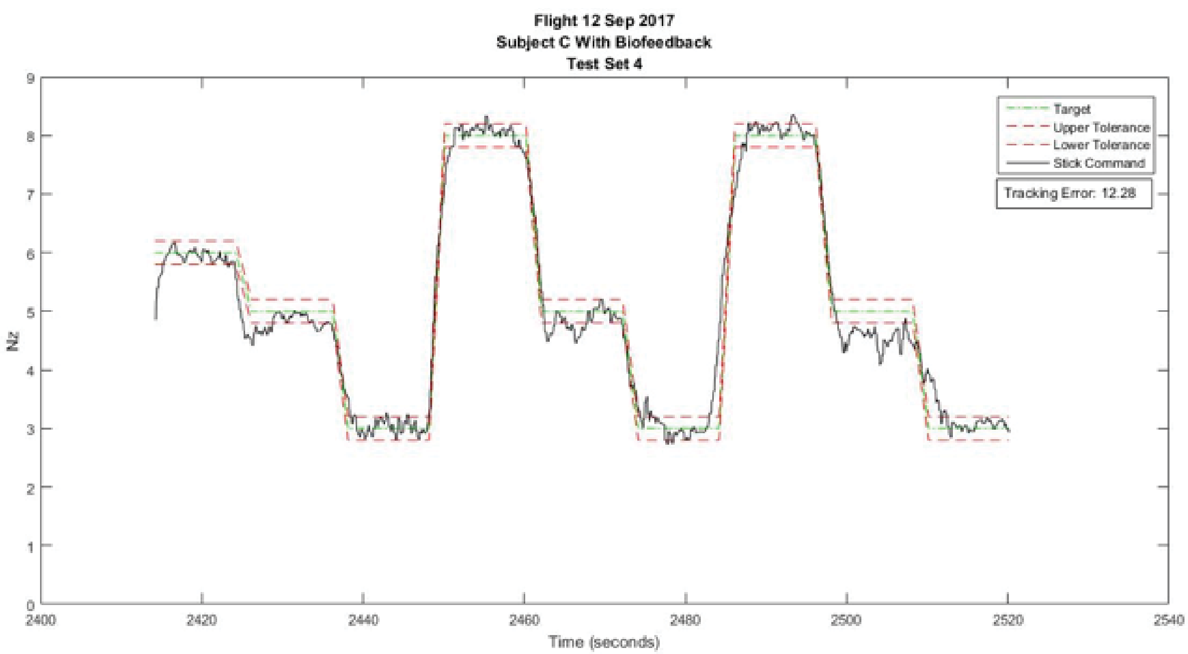

Figure 39: Phase 3 Subject C Flight G-Tracking Error With Biofeedback

Subjects A, B, and C were the test pilots (TPs) on the test team and were the only test subjects for Phase 4 flight tests. Thirteen total flights were conducted and data from nine flights were used. All data from four other flights were discounted since the entire flight profile (all four test sets) was not completed due to fuel or early return for emergency procedures. Each test subject flew one flight without biofeedback and two flights with biofeedback. Data was lost for one of Subject A's flights with biofeedback.

Statistical results are displayed in Table 14 below. For this statistical test, the null hypothesis states there is no statistical difference between G-tracking scores when biofeedback was added. In analyzing the P-values listed below, it can be surmised that with P-values greater than 0.05, Subjects A and C G-tracking scores do not show statistical differences and it can be stated there was a failure to reject the null hypothesis. Restated, Subjects A and C did not show statistically significant improvement between G-tracking errors when biofeedback was added, but in line with Figure 40, improvement was observed. Looking at Subject B's G-tracking score, with a P-value less than 0.05 the null hypothesis was rejected and a statistical difference was noted. Restated, Subject B showed a statistically significant improvement when %HRR biofeedback was provided. As seen in Figure 40 below, the primary variances in G-tracking performance were attributed to individual subjects, and could not be definitively linked to the presence of biofeedback.

Table 14: Phase 4 G-Tracking T-Test Without vs. With Biofeedback

T-Test P Values	
Subject A	0.46
Subject B	0.02
Subject C	0.15

Figure 40: Subject A - C Phase 4 G-Tracking Total Error Scores

Consistent with previous observations in Phase 3, test subject comments again noted that learning effect of the task could have led to decreased task difficulty. Subject B commented on this effect directly saying, "cognitive ability was assessed as greater than the previous flight," suggesting the influence of additional exposures to the task may have influenced learning effect and increased tolerance to the high-G environment. Subject B also commented that, "biofeedback wasn't considered continuously during many of the test sets because of other tasks were deemed more important." This is in line with comments from other pilots that were too concerned with completing cognitive tests, managing airspace, and assessing energy requirements to always utilize the biofeedback display.

4.4.5 STO 7: Evaluate Human Systems Integration of Biofeedback Display

As highlighted in Table 7 of this chapter, STO 7 aimed to evaluate the human system integration (HSI) and usability of the GETAC biofeedback display in cockpits of fighter aircraft. Each subject was instructed to assess the usability of the display during all Phase 3 and 4 testing. Results were assessed to provide recommendations for future design changes. A picture of the cockpit set up and GETAC biofeedback display as viewed from the pilot's perspective is seen in Figure 41 below.

Figure 41: F-16 Internal Cockpit Perspective with Biofeedback Display

All test subjects completed surveys after centrifuge and flight tests using a common usability scale in accordance with the 412th Test Wing Six-Point General Purpose Scale located in Appendix I. The main section of the scale is seen in Figure 42 below.

Scale Value	Response Alternatives	Definitions
1	Very Unsatisfactory	Task cannot be performed or the item is unusable or unsafe. Mission/Task not accomplished due to equipment deficiencies or procedural limitations.
2	Unsatisfactory	Major problems encountered. Task accomplished with great difficulty or accomplished poorly. Significant degradation of mission/task accomplishment or accuracy.
3	Marginally Unsatisfactory	Minor problems encountered. Task accomplished with some difficulty. Some degradation of mission/task accomplishment or accuracy.
4	Marginally Satisfactory	The item or task meets its intended purpose with some reservations. Meets minimum requirements to accomplish mission/task.
5	Satisfactory	The item or task meets its intended purpose; it could be improved to make it easier or more efficient.
6	Very Satisfactory	The item or task is fine the way it is; no improvement required.

Figure 42: 412th Test Wing Six-Point General Purpose Scale

4.4.5.1 MOP 1: Usability of Biofeedback Display

Evaluations of survey numerical value ratings provided by all subjects were averaged to determine a mean score rating and resultant associated impact. Figure 43 below shows the overall mean scores provided by each test subject. Additionally, two aircrew flight equipment (AFE) personnel who participated in setting up and fitting the display also completed a survey assessment for a holistic overview of the GETAC. AFE results were not included in the calculation of the final operator mean usability scores since they were not directly involved with display assessments for centrifuge or flight tests.

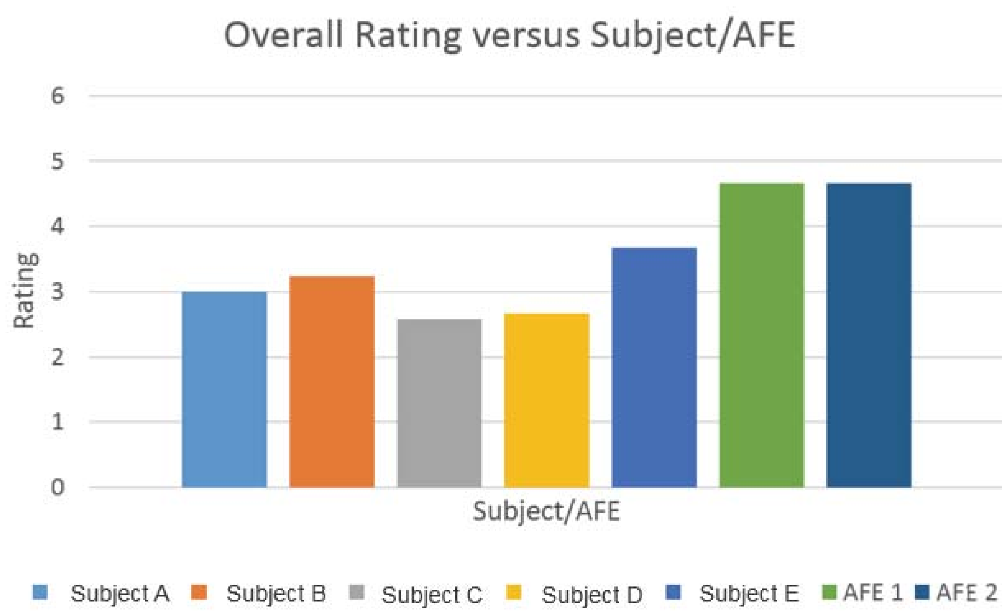

Figure 43: Biofeedback Display Mean Usability Ratings by Subject

Test subjects assessed the GETAC biofeedback display during centrifuge and flight tests. In both environments, subjects considered human factors and usability before and after high-G maneuvering. Specific usability evaluations were taken in terms of display format, readability, fit, comfort, jitter, distortion, visual access, information, controls and perceived workload required for display use. Definitions of each of these areas are included with the survey forms found in Appendix J. Associated impacts to mission effectiveness and flight safety were noted through additional comments.

Subjects A through E were equipped with and assessed GETAC biofeedback display usability during Phase 3 centrifuge tests. Additionally, as the team TPs subjects A, B and C also assessed GETAC biofeedback usability during Phase 4 test flights. All surveys were consolidated, by subject, and values were averaged and tabulated below in Table 15. All completed surveys can be found in Appendix J.

Table 15: Subjects A-E Biofeedback Display Usability Ratings

Factor	Subject					Subject Mean	AFE Ratings		AFE Mean
	A	B	C	D	E		AFE 1	AFE 2	
Format/Readability	3	2.7	2.5	2	2	**2.4**	5	5	**5**
Fit/Comfort	4	5	3	4	6	**4.4**	5	5	**5**
Jitter/Distortion	4	3.3	2.5	4	5	**3.8**	4	4	**4**
Visual Access	2	2.7	3	2	3	**2.5**	4	4	**4**
Information	3	3	3	3	4	**3.2**	6	6	**6**
Controls	2	2.7	1.5	1	2	**1.8**	4	4	**4**
					Test Subject Mean:	**3.0**	**AFE Mean:**		**4.7**

The average of these data indicate a Marginal rating with a Moderate task impact in accordance with the 412th Test Wing scale. Further justifications for the deduced rating and task impact are reflected in the subject comments. General trends in subject comments noted during flight test that glare from the sun impeded the ability to read information from the GETAC display which was further exacerbated by the %HRR information being difficult to read due to font size, relative to screen size. Additionally, all test subjects commented on the "noise" of %HRR figures jumping between excessive values. Subject B stated they, "had to compensate for the noisy data by assessing the %HRR value for several seconds and produce a mental average %HRR." Finally, the position of the GETAC display below the test subject forward field of view (FOV) required subjects to rotate their head downwards, removing attention from the F-16

Heads-Up-Display (HUD), losing access to primary flight information such as airspeed and altitude. Between test sets, several test subjects stated degradation in aircraft flying accuracy due to the "look down" requirement of the GETAC to obtain data.

Setup of the GETAC system was not intuitive, required complex directions, and was uncomfortable to fit and remove due to electrodes attached to the test subject's chest. During setup, multiple wires were required to be fitted around AFE gear in a methodical and standardized manner to avoid entanglement and inadvertent disconnect of devices during centrifuge and flight tests. This process was complex and time consuming. Additionally, after the subjects had been fitted, due diligence still had to be taken to ensure no wires caught on objects during enter and exit of the centrifuge and aircraft. This induced increased workload and physical effort for the test subjects and slowed the process of centrifuge and flight test conduct. In terms of safety, subjects noted due to the bulkiness of the GETAC, emergency egress of the aircraft would potentially be compromised and slow down the egress time. During centrifuge and flight test several test subjects each commented that the GETAC would not be suitable for operational use during basic fighter maneuvers (BFM) engagements due to fatigue and strain on the subject's neck during high-G maneuvers. A picture of the cockpit set up and GETAC biofeedback display as viewed from the pilot's perspective is seen in Figure 43 below.

A major limitation was the inability for the GETAC to record and store HR data. This limitation significantly influenced test conduct and how the test team collected biofeedback data. During with biofeedback tests, subjects had to verbalize their display-presented %HRR value both upon completion of a previous test set and prior to commencing the next test set. The additional time to read the %HRR value reduced the usable time for the subject to complete cognitive assessment tasks and increased overall rest time penalty as discussed previously in this chapter and in Chapter 5.

4.4.6 STO 8: Collect Aircrew Mounted Physiologic Sensor Suite (AMPSS 3.0) Data

As highlighted in Table 7 of this chapter, STO 8 was a simple "ride along" objective added to facilitate data collection for AMPSS 3.0. Subjects A and C collected data only during Phase 3. The F-16 System Program Office (SPO) ultimately did not clear the AMPSS for full airworthiness because windblast testing had not being completed, thus eliminating AMPSS 3.0 from being incorporated into Phase 4 execution.

Additional evaluations of the HSI were conducted through subject surveys based on the 412 TW Six-Point General Purpose Scale introduced in STO 7 of this chapter, seen in Figure 39, and located in Appendix I. Results were assessed to provide recommendations for future utility. In addition to aircrew evaluations, an AFE technician with considerable experience of previous AMPSS model trials (AMPSS 1.0, 2.0 & 2.5) was available to complete a survey while fitting the aircrew with AMPSS 3.0. All surveys were consolidated and tabulated below in Table 16 and 17 below. Detailed completed surveys can be found in Appendix K.

Table 16: Subject A and C AMPSS Usability Ratings

Factor	Subject	
	A	C
Preflight	5.9	6
Execution	5.9	6
Postflight	6	6
General	5	6
MEAN	5.85	

Table 17: AFE Technician AMPSS Usability Ratings

Factor	AFE
Installation	6
Manual: Instructions	4
Preflight	3
Postflight	6
Reliability	5
Maintainability	5
Cleaning/Repair	6
Manual: Cleaning	5
Remove from hose	6
OVERALL	5
MEAN	5.1

Test Pilot (TP) subjects A and C assessed the hardware as Satisfactory with negligible task impact. Important to note, Subject C had experience testing the previous version (AMPSS 2.5). Subject A had no prior experience with any AMPSS system. These assessments are further justified by operator comments and numerical metrics on the subject surveys.

General comments regarding AMPSS from an aircrew perspective described AMPSS as slightly bulkier than a non-AMPSS configuration but did not hamper ability to ingress or egress the representative F-16 cockpit within the centrifuge gondola. Although acceptable, a smaller, CRU-60–AMPSS integrated unit would be better. During high-G centrifuge profiles, the AMPSS was assessed not to interfere or cause discomfort to the operating aircrew and had the same functionality of a standard CRU-60 connector.

It was noted by the AFE technician that AMPSS 3.0 ISB (Inhale Sensor Block) contained all sensors within the in-line assembly, which connected to the hose O_2 connector, and CRU-60/P connector. Furthermore, the AIMS (Aircrew Integrated

Monitoring System) ISB operator user manual was very detailed and comprehensive. However, it didn't include the complete AMPSS 3.0 suite of components to include the Exhale Sensor Block (ESB).

During preflight, the ISB partial pressure of oxygen (ppO_2) sensor component required a preflight sensor calibration in a humidity level less than 3% to operate efficiently. This required the complete ISB unit to be inserted in a humidity wicking substance prior to flight, which was time consuming and required materials not located in a standard AFE shop. During centrifuge trials, reliability comparison to an unmodified system was all that was tested. No problems were encountered, and data were collected. During post flight inspection, AMPSS 3.0 cleaning by AFE personnel is limited to only the exterior of the ISB component as specified by the user manual. This could present potential limitations, as the user manual also did not specify repair instructions. Essentially, the whole unit would need to be sent away for repairs or a complete unit replacement. Additionally, it was noted disconnection of the AMPSS 3.0 from CRU-60/P connector was simple and intuitive.

In summary, AMPSS 3.0 HSI has vastly improved over baseline 1.0, 2.0, and 2.5 model functionality. Form factor was greatly reduced and did not impact aircrew ingress, egress, or execution of basic flight functions. User interface is extremely basic (single LED). Data were successfully gathered regarding the HSI of the device. However, further flight testing regarding functionality will need to occur.

4.5 Chapter Summary

This chapter opened with a reminder of the research question, a reiteration of the motivation behind real-time biofeedback to operators of high performance aircraft, and recap of the STOs and MOPs. Next, a guided discussion covered the results and analysis of the four research phases. Results from Phase 1 led to a decision to continue use of the PECGU as the primary HR sensor for Phases 2, 3, and 4. The use of AMPSS 2.5 was discontinued and the project was scoped to include just cardio metrics. Additionally, emphasis was placed on increasing centrifuge profile exertion (total G) and tracking task difficulty (tracking under G) for Phase 3 testing. Phase 2 led to successful collection of HR_{rest} and HR_{max} values for Subjects A through E; a necessity to develop subject-specific %HRR scales for incorporation into Phases 3 and 4.

In Phases 3 and 4, STO 3 analysis of PECGU data was not proven to have a statistically significant difference from KBRWyle data. Variability in the Garmin data from both the PECGU and Wyle data was observed, but the Garmin did follow the same rise and decline trends as the PECGU and KBRWyle data. Furthermore, it was determined there was no statistically significant difference in cognitive response times and accuracy during without vs. with biofeedback testing.

Analysis of mean Borg RPE scores in STO 4 revealed a non-significant average difference between with and without biofeedback tests. These results and lack of statistically significant difference can primarily be pointed to the small sample size. In all subjects, Borg RPE scores tended to increase as %HRR increased. However, this increase was not statistically significant enough to draw an exact correlation between %HRR and subject perceived exertion.

Analysis of STO 5 showed that during with biofeedback tests, subjects were required to perform key additional steps between high-G test sets that were not required during without biofeedback test sets. Lower rest times and better scores during without biofeedback tests may be attributed to this aspect of test conduct and not specifically lack of biofeedback augmentation.

Results from STO 6 indicated statistically significant improvement in centrifuge tracking task performance with biofeedback in only one of four subjects. Airborne G-tracking performance did improve in all three subjects with the addition of biofeedback, but only one subject showed a statistically significant improvement. Interestingly, Subject B was the individual that showed statistically significant improvement in both centrifuge and airborne tracking with the augmentation of biofeedback.

STO 7 evaluation of the GETAC biofeedback display revealed a Marginal rating with a Moderate task impact. Overall, the system is still in early stages of development and presents several HSI challenges to the operator.

STO 8 analysis showed AMPSS 3.0 HSI had vastly improved over baseline 1.0, 2.0, and 2.5 functionality. The form factor was greatly reduced and did not impact aircrew ingress, egress, or execution of basic flight functions. The user interface was extremely basic; yet further flight tests regarding functionality will need to occur.

Chapter 5 expounds on the derived conclusions and recommendations for future testing identified based on the results and analysis discussed in this chapter.

5. Conclusions and Recommendations

5.1 Chapter Overview

This chapter describes the principle conclusions and recommendations of the four phases of this research. Discussion is addressed in a chronological format following the Specific Test Objectives (STOs) and Measures of Performance (MOPs) outlined in previous chapters and Table 18 below.

Table 18: Specific Test Objectives (STOs) and Measures of Performance (MOPs)

Phase 1 (C1)	**Initial hardware and subject centrifuge trials**
	STO 1: Assess initial hardware and test profile
	MOP 1: Cardiorespiratory response
	MOP 2: Tracking performance
	MOP 3: Workload Level
	MOP 4: Hardware accuracy
Phase 2 (L1)	**Laboratory VO_{2max} testing**
	STO 2: Determine operator peak physiologic output
	MOP 1: Maximal Oxygen Consumption (VO_{2max})
Phase 3 (C2)	**Training and build-up approach centrifuge testing**
Phase 4 (F1)	**Flight testing**
	*Combined STOs and MOPs for phases 3 and 4
	STO 3: Determine operator PC state
	MOP 1: Percentage Heart Rate Reserve (%HRR)
	MOP 2: Portable ECG Unit (PECGU) Accuracy
	MOP 3: Cognitive State
	STO 4: Determine the effect of providing biofeedback on operator PC state awareness
	MOP 1: Awareness of PC state without %HRR biofeedback
	MOP 2: Awareness of PC state with %HRR biofeedback
	STO 5: Determine effect of providing biofeedbaack on decision-making
	MOP 1: Decision-making without %HRR biofeedback
	MOP 2: Decision-making with %HRR biofeedback
	STO 6: Determine effect of providing biofeedback on tracking performance
	MOP 1: Centrifuge tracking task accuracy without biofeedback
	MOP 2: Centrifuge tracking task accuracy with biofeedback
	MOP 3: Airborne G-tracking accuracy without biofeedback
	MOP 4: Airborne G-tracking accuracy with biofeedback
	STO 7: Evaluate human system integration of biofeedback display into fighter cockpit
	MOP 1: Usability of display
	STO 8: Collect Aircrew Mounted Physiologic Sensor Suite (AMPSS 3.0) Data

5.2 Phase 1 (C1): Initial Hardware and Subject Centrifuge Trials

5.2.1 STO 1: Assess Initial Hardware and Test Profile

As stated in Chapter 4, the Zephyr BioHarness 3.0 (Zephyr) was accurate on 3 of 4 subjects, and showed fair correlation in Subject 1. The Portable Electrocardiogram Unit (PECGU) was accurate on 3 of 4 subjects, but showed poor correlation in Subject 6. The Elbit Systems Canary Pilot Health Monitoring System (Elbit) was inaccurate on 3 of 4 subjects, but showed good correlation in Subject 5. In summary, both the Zephyr and PECGU were usually in agreement with Wyle. The Elbit was usually not in agreement with the other sensors. Additionally, the Elbit sensor was inaccurate and occasionally 180 degrees out-of-phase with Wyle "truth source" during high-G test points, but not at low-G test points. Based on these results, the PECGU hardware prototype was deemed valid to progress as the primary heart rate (HR) sensor.

Recommendations for future research based on conclusions of this STO are incorporated into the Phase 3 and 4 sections of this chapter.

5.3 Phase 2 (L1): Laboratory VO_{2max} Testing

5.3.1 STO 2: Determine Operator Peak Physiologic Output

Resting HR (HR_{rest}) and maximum HR (HR_{max}) values were accurately captured for subjects A through E and the necessary data were available to develop subject-specific percentage heart rate reserve (%HRR) scales for incorporation into Phases 3 and 4.

5.3.1.1 STO 2 Recommendations

Recommendations for future testing include a more detailed quantitative log of test subject background to include sleep history, nutrition, hydration, and physical fitness.

This information will provide more context for each subject and potential insight into correlations between subject background and cardio metrics.

5.4 Phase 3 (C2) and Phase 4 (F1): Centrifuge and Flight Testing

5.4.1 STO 3: Determine Operator PC State

5.4.1.1 MOP 2: PECGU Accuracy

The results suggest that subjects could use the PECGU as an accurate data source in flight for %HRR biofeedback. The variability in the Garmin Fenix 3 Sapphire HR Monitor Watch (Garmin) data from the PECGU and Wyle data was likely due to the source of HR measurement in the Garmin. The Garmin uses an optical wrist-mounted HR sensor under the watch bezel. It is assessed that the nature of the test conduct (high-G exposure) could have an impact on optical HR measurements at the wrist and a follow-on effect on data quality.

5.4.1.2 MOP 2 Recommendations

Recommendations for future testing include further development of in-flight recording and storage of HR in the PECGU. The Garmin showed limitations when compared against the KBRWyle Science, Technology, and Engineering Group (KBRWyle) Electrocardiogram (ECG) and was used as a "work-around" so that some HR data could be collected in flight.

5.4.1.3 MOP 3: Cognitive State

Percentage Heart Rate Reserve, %HRR, is not a good sole predictor of cognitive state. Code accuracy appeared to show correlation with %HRR, but was potentially influenced by task environment (centrifuge vs. flight). Test subjects noted in daily flight reports the increased difficulty in code recall during flight test (due to workload) compared to centrifuge test, despite often operating at lower %HRR values. Subjects had increased cognitive workload during fight tests (airspace management, radio calls, setting aircraft parameters for subsequent test sets, etc.) compared to centrifuge tests and baseline ground evaluations.

5.4.1.4 MOP 3 Recommendations

Recommendations for future research include further investigation into differences observed with cognitive recall in the centrifuge vs. flight based on workload. A much larger sample size is needed to show statistical significance. More robust testing in the centrifuge up front could provide cost savings and more data. As previously stated, KBRWyle centrifuge programming limitations did not allow for subjects in Phase 3 testing to have direct control over gondola G. With research justification and more funding this capability may provide added workload challenges and more insight into cognitive limitations under G.

5.4.2 STO 4: Determine Effect of Biofeedback on Operator PC State Awareness

5.4.2.1 MOPs 1 and 2: Awareness of PC State Without and With Biofeedback

Test subject data analysis points to the finding that there was no statistically significant difference between without vs. with biofeedback during subject's subjective assessments of PC state (via Borg RPE scores). Despite variability in Borg RPE score means, a non-parametric median test between the two samples proves that this difference was not statistically significant (Kruskal Wallis Chi-square p-value =0.2522). These results and lack of statistically significant difference can primarily be pointed to the small sample size.

Variations in scores were due to methods and individual test subject traits, not specifically utilization of biofeedback. This presents a complicated problem for a team attempting to tailor an interface to a specific individual as each person requires a custom tailored profile to accurately display biofeedback information that captures the unique attributes of that individual's PC state and perceived exertion compared to that of a different subject.

Additionally, subjects noted that when their mental workload increased in Phase 4, such as coordinating airspace, communications, establishing test set parameters and the combined functions of piloting a high performance aircraft; their Borg RPE scores may have been effected (increased).

Hence, while Borg RPE scores in the maximal oxygen consumption rate (VO_{2max}) test were primarily attributed only to physical exertion of the running treadmill test, during Phase 3 and 4 testing other factors such as physical discomfort, G-strain, air hunger, and task loading likely contributed to an increase in Borg RPE scores at lower %HRR values.

5.4.2.2 STO 4 Recommendations

Future testing recommendations include incorporating larger sample sizes, which are needed to show statistical significance, and may draw correlations to the effect of biofeedback on Borg RPE and physiological and cognitive (PC) state awareness. More robust testing in the centrifuge up front could provide cost savings and more data.

As previously stated in STO 3, recommendations for future research could include further investigation into differences observed between the centrifuge vs. flight, but in this instance focus should key on subject perceived physical exertion with changing mental task loadings. These differences are pervasive based on subject test environment as we saw in comparisons between Phases 2, 3, and 4.

More robust data mining from a wide array of PC sensors could be used to develop unique subject profiles with more informative individualized biofeedback displays beyond simply HR metrics.

5.4.3 STO 5: Determine Effect of Biofeedback on Decision-Making

5.4.3.1 MOPs 1 and 2: Decision-Making Without and With Biofeedback

No statistical significance was found to support that subject decisions and elected rest time changed with respect to testing with or without biofeedback. Variations in scores were due to methods and individual test subject traits, not specifically utilization or non-utilization of biofeedback. Additional required steps during with biofeedback tests resulted in "added" rest time and thus a penalty to overall score. Lower rest times and better scores during without biofeedback tests may be attributed to this aspect of test conduct and not specifically lack of biofeedback augmentation.

5.4.3.2 STO 5 Recommendations

Future testing should attempt to control as many variables as possible through test conduct. Phase 3 and 4 testing required a few "work around" procedures (to gather necessary data, such as verbalizing %HRR values since PECGU data was not recorded. Mature hardware and capitalizing on modeling and simulation in advance can pay dividends during costly test and research.

5.4.4 STO 6: Determine Effect of Biofeedback on Tracking Performance

5.4.4.1 MOPs 1 and 2: Centrifuge G-Tracking Without and With Biofeedback

No discernable trend was observed, possibly due to a learning effect. The one condition in which a statistically significant improvement was shown was on Subject B's second of two centrifuge tests. Previous Phase 3 exposures could have made the G-tracking task easier to accomplish on subsequent runs regardless of the presence of biofeedback.

5.4.4.2 MOPs 3 and 4: Airborne G-Tracking Without and With Biofeedback

All three subjects did show improved G-tracking scores during with biofeedback flight tests, but only one out of three subjects showed a statistically significant improvement with biofeedback flight tests. The only subject to show a statistically significant improvement stated the biofeedback display wasn't being considered when making the decision to start the next test set. It appears that improvements in G-tracking scores are more likely attributed to added exposures of the task, test conduct, and other flight-related stressors such as airspace management and traffic avoidance in the high-G environment.

5.4.4.3 STO 6 Recommendations

As previously stated, future recommendations for this STO need to capitalize on a much larger sample size of subjects. Additionally, subjects need to be thoroughly familiar with the task to remove any learning effect. This presents a challenge when funding and time are often limited. However, at least a two-week trip to the centrifuge before burning jet fuel during flight tests may mitigate some of these challenges.

5.4.5 STO 7: Evaluate Human Systems Integration of Biofeedback Display

5.4.5.1 MOP 1: Usability of Biofeedback Display

Overall analysis of both numerical and subject comment metrics indicated usability of the biofeedback display to the test subject was accessed Marginally Unsatisfactory in accordance with Appendix J. Specific analysis of general fit and comfort of the display was assessed to be Marginal with a Moderate impact to task and mission.

For operationally representative tasks such as high-G basic fighter maneuvers (BFM), a pilot requires continuous "eyes out" time to ensure no loss of sight of the adversary. At current design state, the GETAC display does not offer this capability due to the requirement for the pilot to look down and shift focus from the primary task while attempting to interpret the displayed biofeedback data. Additionally, extreme head movements during high-G maneuvers are typically reduced to the minimum extent practical to reduce fatigue and long-term neck and health issues.

5.4.5.2 STO 7 Recommendations

The following recommendations are provided for future research using a biofeedback display. First, the display/information should be incorporated within the forward pilot field of view (FOV) with appropriately sized font. This will alleviate the operator from a "look down requirement" during critical phases of flight to assess biofeedback and provide a higher sample rate for the subject. Second, a smoothing algorithm should be incorporated into future designs to allow for quick and precise interpretation of data. This will reduce dwell time by operators to interpret the data, provide increased fidelity of collected data points, and lead to less interference with overall test conduct. Finally, internalization of wires and improved data storage capability will increase safety and provide more robust data analysis capability. Further analysis is discussed in the Military Utility section of this chapter.

5.4.6 STO 8: Collect Aircrew Mounted Physiologic Sensor Suite (AMPSS 3.0) Data

Overall comparison of the Aircrew Mounted Physiologic Sensor Suite (AMPSS) 3.0 from baseline mask installation, pre-flight, post-flight, maintenance, and uninstallation function was relatively easy and satisfactory. The AMPSS 3.0 was very quick and easy to install and a considerable improvement from AMPSS 1.0, 2.0 and 2.5. However, no ESB (Exhale Sensor Block) was available to evaluate during Phase 3 tests.

5.4.6.1 STO 8 Recommendations

Of upmost importance, full airworthiness needs to be pursued through the F-16 System Program Office (SPO) and airborne flight reliability testing of an unmodified system still needs to undergo test and evaluation (T&E). Additionally, ESB diagrams and actual ISB and ESB mounting instructions with pictures will be needed in future versions to complete final evaluations of the AMPSS 3.0.

5.5 Simulated vs. Actual Flight Environment Lessons Learned

Numerous recommendations highlighted in this chapter have emphasized the importance of utilizing centrifuge testing in order to establish larger subject pools, garner statistical significance, and save in research costs. While, these recommendations can provide additional data and save costs, the value of human subject testing in high performance aircraft established in the actual flight environment cannot be overstressed. As observed in STO 4, there are added stressors to PC state awareness and performance in a real flight environment that neither cannot be replicated nor accounted for in simulated environments. Subjects stated a "night vs. day" difference in post-flight reports of code recall and accuracy capability. While this observation may seem obvious in hindsight, it was never considered during experimental design. As humans we continually strive to not repeat the same mistakes, yet in retrospective the common phrase, "how did we not see this coming?" could not be more true.

Simulated environments are inherently limited in their ability to accurately model the system in which they are designed to represent. During Phase 3 testing, subjects noted the ease with which a short-term memory task could be conquered and the subjects could confidently "game the system" via a repeated audio-circulatory loop. As Subject A noted, once the code was given, "I spent the entire time under high-G simply focused on staying awake and repeating the code in my head." No further cognitive processing was dedicated towards maneuvering an aircraft as in Phase 4. The Phase 3 tracking task required minimal added cognitive functions and due to sensory-domain differences, the audio-circulatory code recall did not interfere with visual and fine-motor closed-loop tracking. The net result was a simple code recall task, in no way representative of the added cognitive challenges present in a real flight environment.

Testing in actual environments present added challenges and variables, which are difficult to control, and could lead to false conclusions if striving for simply pure and sanitized data. In traditional engineering practice, statistical rigor and a "numbers don't lie" approach is often undertaken. While these fundamentals are paramount to scientific truth, in human subject testing we must accept that empirical observations and a holistic perspective may provide as much (if not more) value when assessing the uniqueness of an actual versus simulated test environment.

During Phase 4 testing, subjects did not have the luxury of repeating the code in an audio-circulatory loop because doing so was disruptive to the long list of additional tasks and added cognitive workload involved with flying the aircraft. Subject C noted, "I tried to repeat the code, but quickly had to abandon the task" for higher priority cognitive functions. The airborne G-tracking event was a high gain task of continuously closing-the-loop of not just aircraft G, but also altitude, airspeed, Mach, bank angle, and aircraft velocity vector, all while managing airspace, communications, energy for follow-on test sets, etc. Hence, while the centrifuge tracking task can be related to the airborne G-tracking task, in reality the airborne environment adds a long list of coupled cognitive tasks that simply cannot be eliminated or modeled in a simulated environment. As a result, observations during flight testing can be summarized by a witty "explosion of the noise". Subject code recall accuracy was initially vastly worse during flight testing as the added tasks and variables simply could not be overcome. As airspace, communication, and task familiarization increased during second, third, and fourth flights, subjects found ways to compensate and code recall slowly improved.

In summary, centrifuge testing is cheaper, safer, and easier to control or identify specific changes in one parameter. Testing in a real flight environment is more expensive, carries more risk (both safety and technical), and is harder to control variables. However, in human subject testing a picture (flight) can often be worth a thousand words (centrifuge).

5.6 Significance of Research

This research was unique in that it marked the first time a pilot's HR had been accurately measured, processed, and incorporated during flight into a real-time biofeedback display. When compared to the KBRWyle "truth data" ECG, the PECGU proved to accurately measure HR and display %HRR real-time.

Additionally, it has been demonstrated through this research that many of the metrics that were measured did not always prove statistically significant or highlight correlation solely to %HRR. Because of the academic nature of this project, the research sponsor knew of the pre-planned and limited subject pool before testing began. Complete statistical significance of every STO was never the end goal, but rather statistical relevance and empirical observations.

That being said, light has been shed onto the potential value of biofeedback in aerospace systems. The human body is an extremely complex and sophisticated machine, one that cannot be surmised in a single parametric value. Future military utility in biofeedback systems will be realized when a myriad of sensors can be integrated to provide a "whole body" metric with a simple user interface to allow pilots a quick glance at their entire PC state before critical airborne decisions are made.

5.7 Military Utility

When assessing military utility of a real-time biofeedback system for high performance aircraft pilots, total utility will be situation dependent based on mission tasks and tactical execution. Two airborne situations are considered and basic implementation methods are discussed.

5.7.1 Within Visual Range (WVR)

Within Visual Range (WVR) maneuvering, or dogfighting, is a high-G, dynamic, and complex flight environment. Pilot's routinely sustain 4-5 Gs and will intermittently increase G-loading upwards of 8-9 Gs for short bursts of 10-15 seconds. Engagements can last anywhere from 10 seconds to 2-3 minutes. Subsets of WVR maneuvering include: BFM, characterized by just one single aircraft versus another; and aerial combat maneuvers (ACM), which consists of three or more aircraft all within a single visual engagement. These mission sets are often referred to as a “knife fight in a phone booth” whereby the first mistake that a pilot makes is usually their last. A pilot’s attention span is spent almost executively outside the cockpit maintaining visual sight of the adversary, aggressively maneuvering the aircraft to a position of advantage, and controlling sensors/weapons through hands-on-throttle-and-stick (HOTAS) actuations to employ ordnance. WVR execution can be correlated to a much more physically demanding environment and cognition is relegated to quick reactions based on mental sight pictures gained from training and prior experience.

In these scenarios, physiological exertion is high and there is extremely limited cognitive bandwidth. The likelihood of continuous use of a real-time biofeedback display during a WVR engagement may be low, but there may be some added value to biofeedback augmentation leading up to WVR maneuvering. Combat missions in fighter aircraft are sometimes over four hours long, and depending on the mission can be as long as six to eight hours. Increased situation awareness (SA) provided by biofeedback of a degraded PC state due to dehydration, deficient nutrition, physiological exertion, or mental fatigue may be the only objective measures a pilot may have as the critical fight or flight decision is being made. Biofeedback for the pilot during this time could alert them to the fact that they may be tired or in a degraded PC state. How this information is used is a completely different discussion. Hence, in the context of WVR maneuvering a real-time biofeedback system appears to have some promise only in aiding a binary decision tree leading up to WVR maneuvering.

5.7.2 Beyond Visual Range (BVR)

Beyond Visual Range (BVR) maneuvering describes tactical operations that take place, just as the name dictates, beyond visual range and constitute all operations outside the small subset of WVR. In a typical mission is a large majority of a pilot's time and attention is spent in the BVR arena. Aircraft maneuvering can be characterized as more smooth and benign. G loading is typically 1-2 Gs with intermittent increases of 3-4 Gs. A much larger portion of a pilot's attention span is spent with eyes inside the cockpit monitoring displays, controlling sensors, and executing higher-level mission management decisions. BVR execution can be correlated to more top-down cognitive processing. Decisions are still made quickly, but are more deliberate and incorporate a wide-spectrum of information from real-time sensors and networks as well as mission planning prior to takeoff.

Most modern aircraft mission computers contain robust failure mode and aircraft systems monitoring capabilities. Pilots are alerted of degraded weapons, failed sensors, and deficient fuel states. This information is fed-back and incorporated in higher-level mission management decisions. An aircraft tells you when the radar is broken. Why can't it tell you when the human is broken (or degraded)? In BVR maneuvering, a real-time biofeedback system just may prove to have military utility.

In BVR scenarios, biofeedback for the pilot could still alert them to a tired or degraded PC state, however more follow-on time may be available for missionized decisions to be influenced. Furthermore, PC state information shared across a standard formation of four aircraft, may offer even more flexibility within the formation. Awareness of degraded cognitive processing from pilot #3 may warrant switching formation positions with #2 (traditionally a more "follower" role). Biofeedback indicating physiological limitations may temporarily drive the pilot to choose a lower risk decision, vice accepting a higher risk intercept that would normally be conducted.

5.7.3 Methods

Methods in which biofeedback informs the operator should capitalize on the same techniques employed in current integrated aircraft alerting systems. The human system needs to be treated like any other aircraft system (engine, hydraulic, oil, pneumatic, environmental). However, information needs to be presented in an intuitive fashion that is minimally intrusive to the operator.

In order to optimize usability a fine balance needs to be struck between cued inputs and subject attention. In engineering practice, attention has been divided into sustained attention (vigilance decrements occur) and selective attention. In selective attention, as multiple displays are available to operators, switching triggers are driven by either endogenous or exogenous inputs. Endogenous attention is characterized by voluntary focus to an area outside current focus to seek information. Exogenous attention is generated by cued (audio/visual) inputs to force attention from outside the focus area to within a specific area of interest (Wickens, Hollands, Parasuraman, & Banbury, 2012).

Biofeedback content should be incorporated into current displays and available via sub menus. As the time-critical nature of PC state awareness is increased, exogenous inputs such as aural, visual, and tactile cueing should be employed. Operators should not be burdened to "babysit" a biofeedback display and rely on endogenous attention means to monitor PC state information. Information needs to be non-invasive to the operator, but pervasive in nature and readily available when needed and prompted by exogenous cueing.

In the most extreme cases, as physiological loading is boosted and potential for G-induced loss of consciousness (G-LOC) increases, PC state recognition algorithms could inform aircraft systems, trigger a recovery profile, and safely recover the aircraft even prior to current automated ground collision avoidance systems (AGCAS) employed in modern fighter aircraft. Further discussion on of ongoing research in improved systems health monitoring algorithms and the potential incorporation into the human system monitoring is addressed later in this chapter.

5.8 Recommendations for Action

The PECGU-GETAC combination served as an initial prototype to collect HR and display %HRR real-time. As previously stated, in its current configuration there was never intent to satisfy military utility, but rather provide a research platform. Moving forward the following recommendations should be considered to further develop biofeedback both from a research and operational perspective.

Before further development of systems and displays are undertaken, more needs to be learned about PC state in high performance aircraft. People have been trying to understand and categorize cognitive processing and physiological stress in aircraft for years. While this problem will not be solved overnight, opportunities need to be capitalized on now.

There is a wide range of biosensors that should be employed in a massive data collection initiative. Dedicated trips to the centrifuge are not even necessary. Every time a pilot takes off there is an opportunity for free data. As discussed in Chapter 2, ECG, electroencephalography (EEG), cerebral oxygen status (COS), pulse oximetry, ocular response, galvanic skin response, and respiratory response are some of the current objective means for attempting to capture operator PC state. Combined with data and information on subject background, detailed operator profiles could be constructed. Subsequently, a robust data-mining initiative could potentially lead to valuable correlations between key biometrics and PC state. Large variability may exist between subjects. Different airborne missions may yield vastly diverse responses from one biometric to the next. Such an endeavor may take years to fully develop. In the end, there is hope for an individualized, all-inclusive, and data-driven complex weighting algorithm, which ultimately presents a streamlined and intuitive PC state/fatigue index.

5.8.1 Future Research/Designs

As previously discussed, in order to realize the full potential of real-time biofeedback in flight, a mindset shift of treating the human system like every other aircraft system (hydraulic, electrical, engine, fuel, etc.) is necessary. This section ties together the potential for human system monitoring to current research of flight safety and real-time early warning techniques (Javorsek II, Barshi, & Iverson, 2016).

A paper titled, *Enhancing Flight Test Safety with Real-time Early Warning Techniques*, introduces new mathematical methods to identify, characterize, and inform future operators of anomalous patterns of behavior in complex systems. The Inductive Monitoring System (IMS) was utilized by the National Aeronautics and Space Administration (NASA) during the accident investigation in the aftermath of the Columbia disaster in 2003 (Iverson, 2004). In short, IMS takes baseline data formatted into vectors and builds a knowledgebase, whereby numerical techniques characterize system behavior by identifying all regions of a nominal N-dimensional state space. Clustering algorithms are used to recognize patterns and define allowable ranges of boundaries. Extremely high/low values within a cluster can be thought of as borders of a minimum-bounding N-dimensional rectangle. The four different cluster algorithms employed in IMS are seen in Figure 44 below: (a) Euclidean distance; (b) Hierarchical, each cluster subdivided into smaller clusters; (c) K-means (with k = 4) partitions space into four subspaces; (d) Self organizing map, centroids organized into grid structure. IMS employs a hybrid of clustering techniques, which ultimately focus on different ways that intercluster distances are defined, also referred to as the linkage function (Javorsek II et al., 2016).

As knowledgebase is improved new vectors are assessed based on location relative to a cluster's centroid (from previous vectors using K-means clustering method). Distances can be measured using a variety of metrics, but Euclidean has proven most effective. New vectors are either added to previous clusters or assigned to a different cluster. Once all baseline data is processed system performance can be characterized and a normal operating envelope is defined. With a working baseline envelope, IMS can now inform the operator if and how a system is deviating from nominal operations. As new vectors are reported real-time, alerting methods can be tailored from extra vigilance to immediate attention, based on severity. Algorithms and numerical methods like IMS have to potential to unlock critical information, previously hidden within the data (Javorsek II et al., 2016).

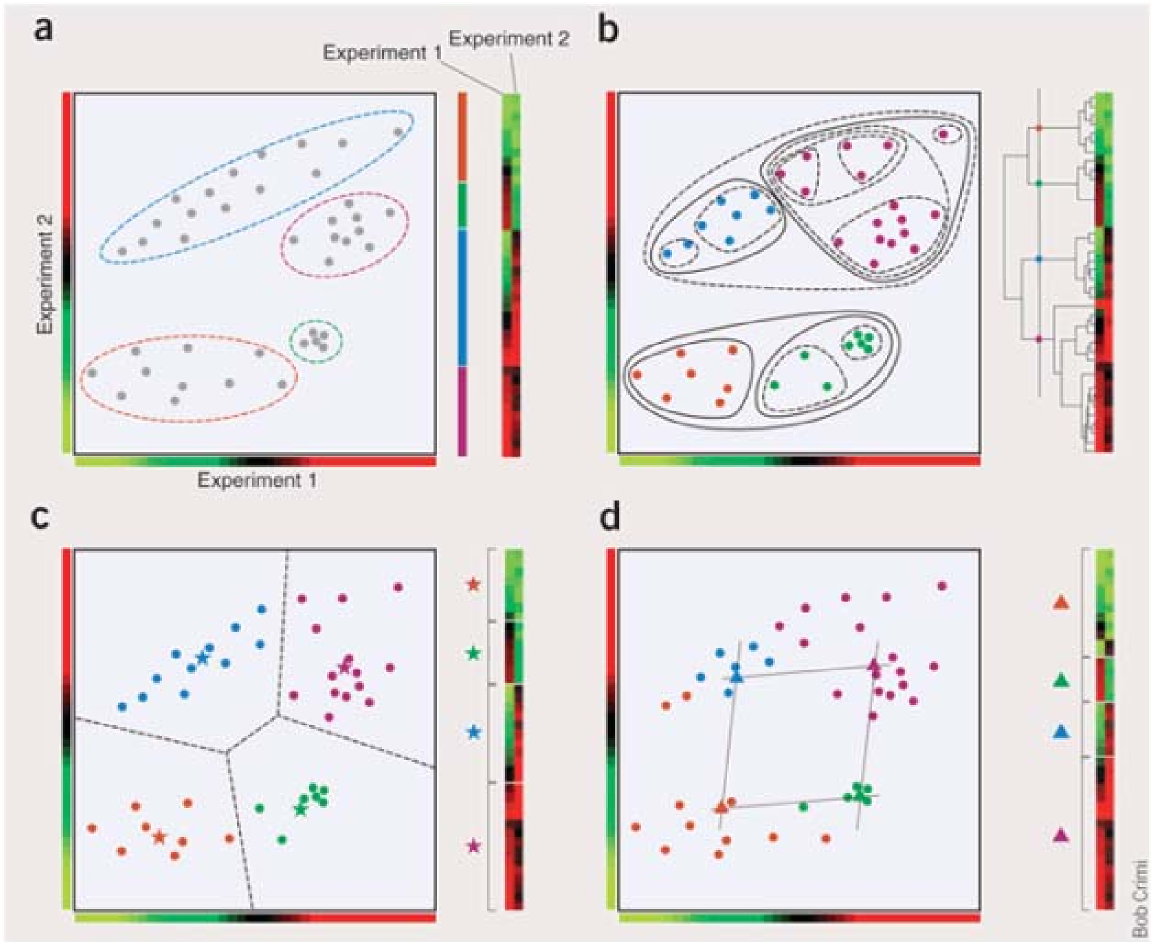

Figure 44: IMS Cluster Algorithms (Javorsek II et al., 2016)

Javorsek, Barshi, and Iverson further introduce a Composite Parameter Display (CPD), whereby a system health monitoring display template of interrelated complex systems may prove more valuable over traditional cockpit displays. CPD incorporates complex parameters (product of two more primary values/parameters) and assigns "custom weighting factors based on the known interrelationships that arise naturally from the subsystem architecture" (Javorsek, et all.).

In the example shown below in Figure 45 (Barshi, 2012), a display developed by the NASA Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) for a UH-60 Blackhawk helicopter included several primary and composite parameters from instrumented engine values. Primary parameters were recorded for power turbine speed (Np), gas generator speed (Ng), engine torque (Tq), and fuel flow (FF). IMS analysis suggested composite parameters and a display was created based on medieval girih tilework. Primary parameters (left and right) were displayed as “petals” at the “flower” center, with subsequent composite parameters shown in outer petals conveying interrelationships and anomalous patterns via color changes. Furthermore, displays can be expanded upon to incorporate other subsystems by connecting adjacent flowers. These interactions within complex subsystems may be the first indications during flight emergencies or mishaps (Javorsek, et all.).

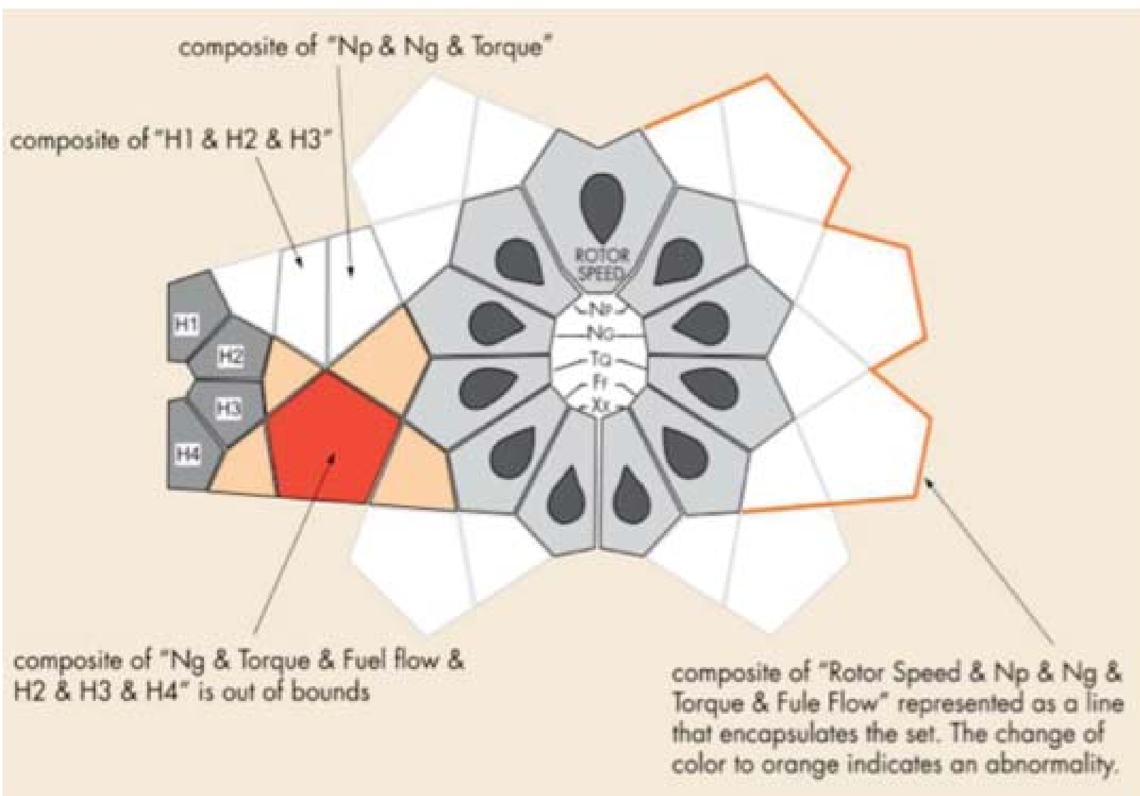

Figure 45: NASA RASCAL’s Medieval Girih Tilework Display (Barshi, 2012)

As highlighted in the above summary of current research efforts in real-time early warning techniques, it is evident there is an avenue to incorporate real-time biofeedback and monitoring of human systems as addressed in this research. A baseline knowledgebase could be created through robust data collection. Algorithms and numerical methods can then be applied real-time to airborne imported data from biosensors. As knowledgebase increased, subject-specific profiles would need to be created. Individual operators would be actively expanding and refining the knowledgebase of their PC state through continued flight operations. While this endeavor may not be trivial, the potential to change how human system health monitoring is implemented and displayed may have tremendous enduring effects to the warfighter.

5.9 Chapter Summary

This chapter opened with a recap of the STOs and MOPs. Second, conclusions and recommendations were expounded upon based on the results and analysis described in Chapter 4. Third, the uniqueness of this research was affirmed in that it marks the first time a pilot's HR has been accurately measured, processed, and incorporated during flight into a real-time biofeedback display. Fourth, implementation methods and analysis and was done of the potential military utility of biofeedback displays in high performance aircraft. Fifth, a call for action was made and the importance of future data collection initiatives was identified. Lastly, ongoing research in real-time early warning algorithms and displays was linked to this research as potential for improving human systems health monitoring via real-time biofeedback.

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Appendix A – Flight Profile

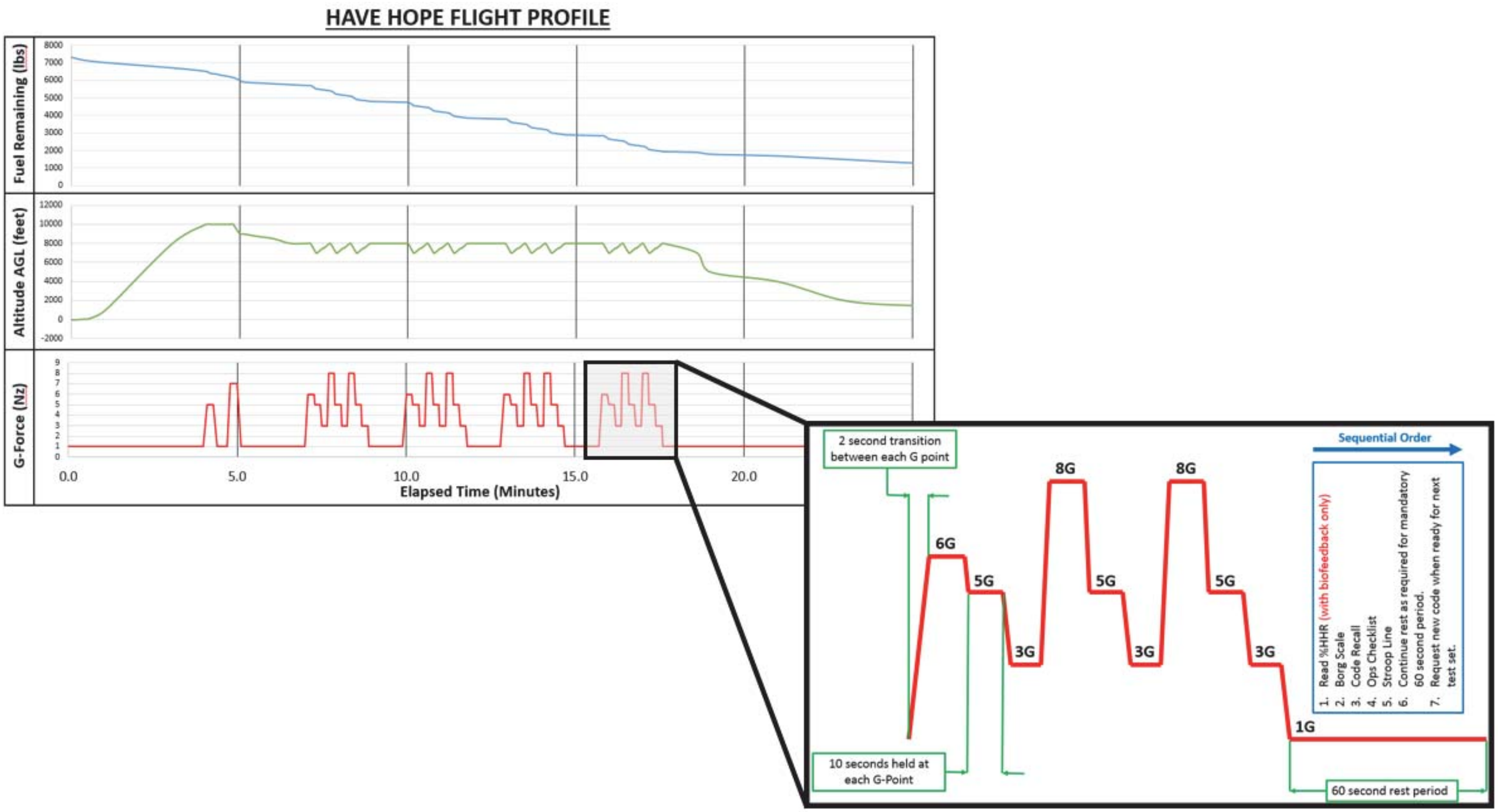


Figure 46: Phase 4 Flight Profile

Appendix B – Phase 3 and 4 Master Data Spreadsheet

Day	Test Subject	Centrifuge /Flight	Data Quality	Bio-feedback	Event	HR Wyle	HR Watch	HR PECGU	%HRR Wyle	%HRR Watch	%HRR PECGU	Borg (0-10)	Code %Accurate	Code Time (s)	Ops Time (s)	Stroop Color %Accurate	Stroop Color Time (s)	Stroop Word %Accurate	Stroop Word Time (s)	Rest Time (s)	Test Score (lower is better)
15-Aug	A	Centrifuge	Good	No	Ground	93	N/A	N/A	21.80%	N/A	N/A	1	100.00%	2.5	24.00	100.00%	8.00	N/A	N/A	N/A	N/A
15-Aug	A	Centrifuge	Good	No	G ex 1	120	N/A	N/A	42.11%	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Aug	A	Centrifuge	Good	No	G ex 2	132	N/A	N/A	51.13%	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Aug	A	Centrifuge	Good	No	Test set 1	140	N/A	N/A	57.14%	N/A	N/A	4	60.00%	4.9	26.00	83.33%	3.00	N/A	N/A	107.00	N/A
15-Aug	A	Centrifuge	Good	No	Test set 2	150	N/A	N/A	64.66%	N/A	N/A	5	60.00%	8	18.40	100.00%	3.20	N/A	N/A	110.00	N/A
15-Aug	A	Centrifuge	Good	No	Test set 3	157	N/A	N/A	69.92%	N/A	N/A	6	60.00%	3.5	19.00	100.00%	2.80	N/A	N/A	94.00	N/A
15-Aug	A	Centrifuge	Good	No	Test set 4	157	N/A	N/A	69.92%	N/A	N/A	7	80.00%	3.6	16.00	100.00%	3.12	N/A	N/A	N/A	5437.58
16-Aug	A	Centrifuge	Good	Yes	Ground	No Data	95	99	No Data	23.31%	26.32%	1	100.00%	4	17.90	100.00%	4.40	N/A	N/A	N/A	N/A
16-Aug	A	Centrifuge	Good	Yes	G ex 1	113.875	119	115	37.50%	41.35%	38.35%	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16-Aug	A	Centrifuge	Good	Yes	G ex 2	147.125	115	142	62.50%	38.35%	58.65%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16-Aug	A	Centrifuge	Good	Yes	Test set 1	150.45	96	155	65.00%	24.06%	68.42%	4	100.00%	1.6	16.00	100.00%	5.00	N/A	N/A	85.00	N/A
16-Aug	A	Centrifuge	Good	Yes	Test set 2	150.45	109	159	65.00%	33.83%	71.43%	6	40.00%	2.9	12.70	100.00%	4.10	N/A	N/A	223.00	N/A
16-Aug	A	Centrifuge	Good	Yes	Test set 3	150.45	104		65.00%	30.08%		6	80.00%	3.3	17.00	100.00%	3.90	N/A	N/A	109.00	N/A
16-Aug	A	Centrifuge	Good	Yes	Test set 4	160.425	106	174	72.50%	31.58%	82.71%	7	80.00%	2.4	17.10	100.00%	4.40	N/A	N/A	N/A	No Data
5-Sep	A	Flight	Good	Yes	Ground	N/A	116	N/A	N/A	39.10%	55.00%	1	60.00%	3.4	18.40	100.00%	3.30	N/A	N/A		N/A
5-Sep	A	Flight	Good	Yes	G ex 1	N/A	137	N/A	N/A	54.89%	65.00%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5-Sep	A	Flight	Good	Yes	G ex 2	N/A	138	N/A	N/A	55.64%	57.00%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5-Sep	A	Flight	Marginal	Yes	Test set 1	N/A	142	N/A	N/A	58.65%	inop	4	60.00%	3.5	16.90	100.00%	3.90	N/A	N/A	99.80	N/A
5-Sep	A	Flight	BAD	Yes	Test set 2	N/A	144	N/A	N/A	60.15%	inop	3	20.00%	3.3	13.70	100.00%	3.90	N/A	N/A	N/A	N/A
5-Sep	A	Flight	BAD	Yes	Test set 3	N/A	123	N/A	N/A	44.36%	55.00%	3	60.00%	3.5	14.80	100.00%	4.50	N/A	N/A	56.50	N/A
5-Sep	A	Flight	No Data	Yes	Test set 4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	No Data
8-Sep	A	Flight	Good	No	Ground	N/A	119	N/A	N/A	41.35%	N/A	1	100.00%	1.9	16.70	100.00%	3.80	100.00%	2.40	N/A	N/A
8-Sep	A	Flight	Good	No	G ex 1	N/A	130	N/A	N/A	49.62%	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8-Sep	A	Flight	Good	No	G ex 2	N/A	134	N/A	N/A	52.63%	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8-Sep	A	Flight	Good	No	Test set 1	N/A	171	N/A	N/A	80.45%	N/A	3	60.00%			100.00%	3.8	100.00%	2.60	84.00	N/A

Day	Test Subject	Centrifuge /Flight	Data Quality	Bio-feedback	Event	HR Wyle	HR Watch	HR PECGU	%HRR Wyle	%HRR Watch	%HRR PECGU	Borg (0-10)	Code %Accurate	Code Time (s)	Ops Time (s)	Stroop Color %Accurate	Stroop Color Time (s)	Stroop Word %Accurate	Stroop Word Time (s)	Rest Time (s)	Test Score (lower is better)
8-Sep	A	Flight	Good	No	Test set 2	N/A	170	N/A	N/A	79.70 %	N/A	4	40.00 %	3.5	13.60	100.00%	3.3	100.00%	2.60	75.00	N/A
8-Sep	A	Flight	Good	No	Test set 3	N/A	163	N/A	N/A	74.44 %	N/A	4	20.00 %	4.5	16.60	100.00%	3.4	100.00%	2.60	73.00	N/A
8-Sep	A	Flight	Good	No	Test set 4	N/A	173	N/A	N/A	81.95 %	N/A	5	20.00 %	2.6	13.80	100.00%	3.1	100.00%	2.90	N/A	602.65
12-Sep	A	Flight	Good	Yes	Ground	N/A	117	N/A	N/A	39.85 %	47.00 %	1	100.00 %	3.4	17.00	100.00%	3.70	100.00%	3.60	N/A	N/A
12-Sep	A	Flight	Good	Yes	G ex 1	N/A	140	N/A	N/A	57.14 %	55.00 %	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12-Sep	A	Flight	Good	Yes	G ex 2	N/A	148	N/A	N/A	63.16 %	75.00 %	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12-Sep	A	Flight	Good	Yes	Test set 1	N/A	155	N/A	N/A	68.42 %	80.00 %	2	40.00 %	3.1	14.40	100.00%	5.40	100.00%	3.30	102.00	N/A
12-Sep	A	Flight	Good	Yes	Test set 2	N/A	169	N/A	N/A	78.95 %	90.00 %	3	100.00 %	3.8	16.90	100.00%	2.90	100.00%		99.00	N/A
12-Sep	A	Flight	Good	Yes	Test set 3	N/A	166	N/A	N/A	76.69 %	85.00 %	3	40.00 %	3.6	14.00	100.00%	4.00	100.00%	3.30	94.00	N/A
12-Sep	A	Flight	Good	Yes	Test set 4	N/A	125	N/A	N/A	45.86 %	90.00 %	4	40.00 %	4.5	18.60	100.00%	4.00	100.00%	4.00	N/A	1136.68
15-Sep	A	Flight	Good	Yes	Ground	N/A	126	N/A	N/A	46.62 %	46.00 %	1	60.00 %	2.3	18.00	100.00%	2.80	100.00%	2.40	N/A	N/A
15-Sep	A	Flight	Good	Yes	G ex 1	N/A	140	N/A	N/A	57.14 %	65.00 %	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Sep	A	Flight	Good	Yes	G ex 2	N/A	120	N/A	N/A	42.11 %	60.00 %	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Sep	A	Flight	Good	Yes	Test set 1	N/A	163	N/A	N/A	74.44 %	80.00 %	3	100.00 %	2.9	17.30	100.00%	3.60	100.00%	2.60	93.00	N/A
15-Sep	A	Flight	Good	Yes	Test set 2	N/A	129	N/A	N/A	48.87 %	80.00 %	4	40.00 %	2.9	14.90	100.00%	3.90	100.00%	2.30	87.00	N/A
15-Sep	A	Flight	Good	Yes	Test set 3	N/A	152	N/A	N/A	66.17 %	78.00 %	4	100.00 %	3.2	13.30	100.00%	3.00	100.00%	3.10	84.00	N/A
15-Sep	A	Flight	Good	Yes	Test set 4	N/A	167	N/A	N/A	77.44 %	87.00 %	4	40.00 %	5.8	16.40	100.00%	4.10	100.00%	3.00	N/A	No Data
15-Aug	B	Centrifuge	Good	No	Ground	111	N/A	N/A	40.14 %	N/A	N/A	1	100.00 %	2.8	16.80	100.00%	6.80	N/A	N/A	N/A	N/A
15-Aug	B	Centrifuge	Good	No	G ex 1	111	N/A	N/A	40.14 %	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Aug	B	Centrifuge	Good	No	G ex 2	133	N/A	N/A	55.10 %	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Aug	B	Centrifuge	Good	No	Test set 1	152	N/A	N/A	68.03 %	N/A	N/A	4	60.00 %	3.8	17.30	83.33%	8.50	N/A	N/A	90.00	N/A
15-Aug	B	Centrifuge	Good	No	Test set 2	150	N/A	N/A	66.67 %	N/A	N/A	5	60.00 %	4.4	17.70	100.00%	9.30	N/A	N/A	92.00	N/A
15-Aug	B	Centrifuge	Good	No	Test set 3	160	N/A	N/A	73.47 %	N/A	N/A	6	0.00%	4.8	14.80	100.00%	4.10	N/A	N/A	75.00	N/A
15-Aug	B	Centrifuge	Good	No	Test set 4	150	N/A	N/A	66.67 %	N/A	N/A	7	20.00 %	8	16.40	100.00%	7.00	N/A	N/A	N/A	1383.62
16-Aug	B	Centrifuge	Good	Yes	Ground	110.8	95	inop	40.00 %	29.25 %	inop	1	100.00 %	2.9	15.30	100.00%	10.50	N/A	N/A	N/A	N/A
16-Aug	B	Centrifuge	Good	Yes	G ex 1	128.44	119	inop	52.00 %	45.58 %	inop	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16-Aug	B	Centrifuge	Good	Yes	G ex 2	132.85	115	inop	55.00 %	42.86 %	inop	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Day	Test Subject	Centrifuge /Flight	Data Quality	Bio-feedback	Event	HR Wyle	HR Watch	HR PECGU	%HRR Wyle	%HRR Watch	%HRR PECGU	Borg (0-10)	Code %Accurate	Code Time (s)	Ops Time (s)	Stroop Color %Accurate	Stroop Color Time (s)	Stroop Word %Accurate	Stroop Word Time (s)	Rest Time (s)	Test Score (lower is better)
16-Aug	B	Centrifuge	Good	Yes	Test set 1	150	139	inop	66.67%	59.18%	inop	4	80.00%	2.2	16.60	100.00%	7.80	N/A	N/A	104.00	N/A
16-Aug	B	Centrifuge	Good	Yes	Test set 2	140	126	inop	59.86%	50.34%	inop	5	60.00%	2.3	20.90	100.00%	5.70	N/A	N/A	90.00	N/A
16-Aug	B	Centrifuge	Good	Yes	Test set 3	140	142	inop	59.86%	61.22%	inop	5	0.00%	7.8	21.80	100.00%	10.90	N/A	N/A	117.00	N/A
16-Aug	B	Centrifuge	Good	Yes	Test set 4	140	143	inop	59.86%	61.90%	inop	6	0.00%	4.7	21.60	100.00%	12.30	N/A	N/A	N/A	9450.87
6-Sep	B	Flight	Good	Yes	Ground	N/A	93	N/A	N/A	27.89%	25.00%	2	100.00%	3.6	27.60	100.00%	7.90	100.00%	9.6	N/A	N/A
6-Sep	B	Flight	Good	Yes	G ex 1	N/A	107	N/A	N/A	37.41%	77.00%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
6-Sep	B	Flight	Good	Yes	G ex 2	N/A	111	N/A	N/A	40.14%	43.00%	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
6-Sep	B	Flight	Marginal	Yes	Test set 1	N/A	104	N/A	N/A	35.37%	46.00%	3	100.00%	3.5	19.40	100.00%	12.70	100.00%	3.80		N/A
6-Sep	B	Flight	Marginal	Yes	Test set 2	N/A	115	N/A	N/A	42.86%	38.00%	4	80.00%	5.9	21.10	100.00%	9.80	100.00%	8.00	118.00	N/A
6-Sep	B	Flight	Marginal	Yes	Test set 3	N/A	92	N/A	N/A	27.21%	26.00%	3	40.00%	3.5	24.50	100.00%	4.00	100.00%	3.90	79.00	N/A
6-Sep	B	Flight	Marginal	Yes	Test set 4	N/A	103	N/A	N/A	34.69%	43.00%	4	40.00%		19.70	100.00%	9.70	100.00%	5.40	N/A	No Data
8-Sep	B	Flight	Good	No	Ground	N/A	111	N/A	N/A	40.14%	N/A	1	80.00%	2.5	25.90	100.00%	6.00	100.00%	5.70	N/A	N/A
8-Sep	B	Flight	Good	No	G ex 1	N/A	115	N/A	N/A	42.86%	N/A	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8-Sep	B	Flight	Good	No	G ex 2	N/A	122	N/A	N/A	47.62%	N/A	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8-Sep	B	Flight	Good	No	Test set 1	N/A	156	N/A	N/A	70.75%	N/A	3	100.00%	2.5	23.40	100.00%	7.90	100.00%	7.00	103.00	N/A
8-Sep	B	Flight	Good	No	Test set 2	N/A	147	N/A	N/A	64.63%	N/A	5	60.00%	2.8	23.60	100.00%	4.60	100.00%	7.80	105.00	N/A
8-Sep	B	Flight	Good	No	Test set 3	N/A	149	N/A	N/A	65.99%	N/A	5	20.00%	5.2	22.30	100.00%	2.90	100.00%	3.50	114.00	N/A
8-Sep	B	Flight	Good	No	Test set 4	N/A	151	N/A	N/A	67.35%	N/A	6	60.00%	2	31.10	100.00%	3.80	100.00%	3.30	N/A	2124.22
11-Sep	B	Flight	Marginal	Yes	Ground	N/A	97	N/A	N/A	30.61%	inop	1	100.00%	1.9	38.00	100.00%	6.70	100.00%	3.00	N/A	N/A
11-Sep	B	Flight	Good	Yes	G ex 1	N/A	102	N/A	N/A	34.01%	31.00%	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11-Sep	B	Flight	Good	Yes	G ex 2	N/A	104	N/A	N/A	35.37%	34.00%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11-Sep	B	Flight	Poor	Yes	Test set 1	N/A	108	N/A	N/A	38.10%	41.00%	3	100.00%	2.40	23.60	100.00%	7.50	100.00%	5.00	No Data	N/A
11-Sep	B	Flight	Marginal	Yes	Test set 2	N/A	107	N/A	N/A	37.41%	32.00%	4	20.00%	7.4	19.90	100.00%	6.30	100.00%	5.00	137.00	N/A
11-Sep	B	Flight	Poor	Yes	Test set 3	N/A	111	N/A	N/A	40.14%	38.00%	5	40.00%	6.8	21.70	100.00%	5.90	83.33%	7.30	No Data	N/A
11-Sep	B	Flight	No Data	Yes	Test set 4	N/A	No Data	N/A	N/A	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data
12-Sep	B	Flight	Good	Yes	Ground	N/A	95	N/A	N/A	29.25%	30.00%	1	100.00%	5.8	22.30	100.00%	7.30	100.00%	6.60	N/A	N/A

Day	Test Subject	Centrifuge /Flight	Data Quality	Bio-feedback	Event	HR Wyle	HR Watch	HR PECGU	%HRR Wyle	%HRR Watch	%HRR PECGU	Borg (0-10)	Code %Accurate	Code Time (s)	Ops Time (s)	Stroop Color %Accurate	Stroop Color Time (s)	Stroop Word %Accurate	Stroop Word Time (s)	Rest Time (s)	Test Score (lower is better)
12-Sep	B	Flight	Good	Yes	G ex 1	N/A	114	N/A	N/A	42.18 %	31.00 %	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12-Sep	B	Flight	Good	Yes	G ex 2	N/A	118	N/A	N/A	44.90 %	34.00 %	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12-Sep	B	Flight	Good	Yes	Test set 1	N/A	119	N/A	N/A	45.58 %	58.00 %	3	40.00 %	6.4	24.30	100.00%	5.9	100.00%	8.4	144	N/A
12-Sep	B	Flight	Good	Yes	Test set 2	N/A	117	N/A	N/A	44.22 %	52.00 %	4	0.00%	7	27.30	83.33%	10.9	100.00%	11.6	126	N/A
12-Sep	B	Flight	Good	Yes	Test set 3	N/A	107	N/A	N/A	37.41 %	32.00 %	4	20.00 %	5.6	28.30	100.00%	2.4	100.00%	4.8	125	N/A
12-Sep	B	Flight	Good	Yes	Test set 4	N/A	109	N/A	N/A	38.78 %	48.00 %	4	20.00 %	7.7	20.60	100.00%	5.3	100.00%	5	N/A	2598.13
14-Sep	B	Flight	Good	Yes	Ground	N/A	86	N/A	N/A	23.13 %	32.00 %	1	100.00 %	1.3	18.90	100.00%	4.90	100.00%	5.90	N/A	N/A
14-Sep	B	Flight	Good	Yes	G ex 1	N/A	105	N/A	N/A	36.05 %	22.00 %	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14-Sep	B	Flight	Good	Yes	G ex 2	N/A	105	N/A	N/A	36.05 %	39.00 %	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14-Sep	B	Flight	Good	Yes	Test set 1	N/A	140	N/A	N/A	59.86 %	68.00 %	3	60.00 %	2.6	18.80	100.00%	3.60	100.00%	3.90	111.00	N/A
14-Sep	B	Flight	Good	Yes	Test set 2	N/A	126	N/A	N/A	50.34 %	63.00 %	3	20.00 %	9.8	20.80	100.00%	3.30	100.00%	4.50	131.00	N/A
14-Sep	B	Flight	Good	Yes	Test set 3	N/A	131	N/A	N/A	53.74 %	61.00 %	4	40.00 %	9.8	28.80	100.00%	4.80	100.00%	3.50	148.00	N/A
14-Sep	B	Flight	Good	Yes	Test set 4	N/A	134	N/A	N/A	55.78 %	43.00 %	5	40.00 %	9.1	25.60	100.00%	9.90	100.00%	5.90	N/A	2223.12
15-Aug	C	Centrifuge	Good	No	Ground	102	N/A	N/A	34.97 %	N/A	N/A	0	100.00 %	1.3	12.00	100.00%	2.60	N/A	N/A	0.00	N/A
15-Aug	C	Centrifuge	Good	No	G ex 1	120	N/A	N/A	47.55 %	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Aug	C	Centrifuge	Good	No	G ex 2	119	N/A	N/A	46.85 %	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Aug	C	Centrifuge	Good	No	Test set 1	131	N/A	N/A	55.24 %	N/A	N/A	4	100.00 %	2.3	8.00	83.33%	3.60	N/A	N/A	76.00	N/A
15-Aug	C	Centrifuge	Good	No	Test set 2	138	N/A	N/A	60.14 %	N/A	N/A	5	100.00 %	2.9	10.20	100.00%	6.00	N/A	N/A	76.00	N/A
15-Aug	C	Centrifuge	Good	No	Test set 3	123	N/A	N/A	49.65 %	N/A	N/A	5	100.00 %	2	10.00	100.00%	10.60	N/A	N/A	65.00	N/A
15-Aug	C	Centrifuge	Good	No	Test set 4	130	N/A	N/A	54.55 %	N/A	N/A	5	100.00 %	2.3	9.70	100.00%	2.00	N/A	N/A	0.00	1865.84
16-Aug	C	Centrifuge	Good	Yes	Ground	85	81	85	23.08 %	20.28 %	23.08 %	0	100.00 %	1.1	10.00	100.00%	6.00	N/A	N/A	0.00	N/A
16-Aug	C	Centrifuge	Good	Yes	G ex 1	102.05	105	93	35.00 %	37.06 %	28.67 %	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16-Aug	C	Centrifuge	Good	Yes	G ex 2	105	115	142	37.06 %	44.06 %	62.94 %	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16-Aug	C	Centrifuge	Good	Yes	Test set 1	120	111	115	47.55 %	41.26 %	44.06 %	4	100.00 %	1.6	8.60	100.00%	2.20	N/A	N/A	71.00	N/A
16-Aug	C	Centrifuge	Good	Yes	Test set 2	117	107	125	45.45 %	38.46 %	51.05 %	4	100.00 %	2.2	9.40	100.00%	7.80	N/A	N/A	72.00	N/A
16-Aug	C	Centrifuge	Good	Yes	Test set 3	122	113	125	48.95 %	42.66 %	51.05 %	5	100.00 %	2	8.60	100.00%	3.60	N/A	N/A	71.00	N/A
16-Aug	C	Centrifuge	Good	Yes	Test set 4	121	110	122	48.25 %	40.56 %	48.95 %	6	100.00 %	1.33	9.10	100.00%	11.00	N/A	N/A		1978.97

Day	Test Subject	Centrifuge /Flight	Data Quality	Bio-feedback	Event	HR Wyle	HR Watch	HR PECGU	%HRR Wyle	%HRR Watch	%HRR PECGU	Borg (0-10)	Code %Accurate	Code Time (s)	Ops Time (s)	Stroop Color %Accurate	Stroop Color Time (s)	Stroop Word %Accurate	Stroop Word Time (s)	Rest Time (s)	Test Score (lower is better)
5-Sep	C	Flight	Good	No	Ground	N/A	N/A	N/A	N/A	N/A	N/A	1	100.00%	1.5	16.90	100.00%	2.00	No Data	No Data	No Data	N/A
5-Sep	C	Flight	Good	No	G ex 1	N/A	N/A	N/A	N/A	N/A	N/A	No Data	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5-Sep	C	Flight	Good	No	G ex 2	N/A	N/A	N/A	N/A	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5-Sep	C	Flight	Marginal	No	Test set 1	N/A	N/A	N/A	N/A	N/A	N/A	3	60.00%	3.1	12.30	100.00%	1.80	No Data	No Data	98.00	N/A
5-Sep	C	Flight	Marginal	No	Test set 2	N/A	N/A	N/A	N/A	N/A	N/A	4	0.00%	1.3	14.10	100.00%	2.20	No Data	No Data	104.00	N/A
5-Sep	C	Flight	Marginal	No	Test set 3	N/A	N/A	N/A	N/A	N/A	N/A	4	100.00%	1.2	21.90	100.00%	3.70	No Data	No Data	100.00	N/A
5-Sep	C	Flight	Marginal	No	Test set 4	N/A	N/A	N/A	N/A	N/A	N/A	4	20.00%	2.3	15.30	100.00%	2.70	No Data	No Data	N/A	No Data
12-Sep	C	Flight	Good	Yes	Ground	N/A	129	N/A	N/A	53.85%	59.00%	1	100.00%	1.5	17.60	100.00%	3.30	100.00%	2.10	N/A	N/A
12-Sep	C	Flight	Good	Yes	G ex 1	N/A	111	N/A	N/A	41.26%	50.00%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12-Sep	C	Flight	Good	Yes	G ex 2	N/A	120	N/A	N/A	47.55%	58.00%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12-Sep	C	Flight	Good	Yes	Test set 1	N/A	120	N/A	N/A	47.55%	58.00%	3	40.00%	4.1	14.20	100.00%	1.80	100.00%	1.80	90.00	N/A
12-Sep	C	Flight	Good	Yes	Test set 2	N/A	123	N/A	N/A	49.65%	57.00%	3	40.00%	1.5	13.00	100.00%	1.50	100.00%	2.30	80.00	N/A
12-Sep	C	Flight	Marginal	Yes	Test set 3	N/A	123	N/A	N/A	49.65%	No Data	4	No Data	No Data	No Data	100.00%	2.00	100.00%	1.70	203.00	N/A
12-Sep	C	Flight	Good	Yes	Test set 4	N/A	131	N/A	N/A	55.24%	61.00%	5	40.00%	5.8	12.00	100.00%	2.60	100.00%	1.80	N/A	1673.97
15-Sep	C	Flight	Good	No	Ground	N/A	99	N/A	N/A	32.87%	N/A	1	100.00%	1.3	12.80	100.00%	2.10	100.00%	2.40	N/A	N/A
15-Sep	C	Flight	Good	No	G ex 1	N/A	116	N/A	N/A	44.76%	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Sep	C	Flight	Good	No	G ex 2	N/A	123	N/A	N/A	49.65%	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15-Sep	C	Flight	Good	No	Test set 1	N/A	122	N/A	N/A	48.95%	N/A	2	100.00%	1	13.30	100.00%	4.90	100.00%	2.00	71.00	N/A
15-Sep	C	Flight	Good	No	Test set 2	N/A	118	N/A	N/A	46.15%	N/A	3	100.00%	1.3	12.40	100.00%	4.50	100.00%	3.50	76.00	N/A
15-Sep	C	Flight	Good	No	Test set 3	N/A	127	N/A	N/A	52.45%	N/A	3	40.00%	3.9	12.80	100.00%	2.80	100.00%	2.10	80.00	N/A
15-Sep	C	Flight	Good	No	Test set 4	N/A	124	N/A	N/A	50.35%	N/A	3	40.00%	5.7	9.80	100.00%	2.80	100.00%	2.50	N/A	527.98
18-Sep	C	Flight	Good	Yes	Ground	N/A	104	N/A	N/A	36.36%	37.00%	1	100.00%	1.1	13.10	100.00%	2.00	100.00%	2.40	N/A	N/A
18-Sep	C	Flight	Good	Yes	G ex 1	N/A	115	N/A	N/A	44.06%	40.00%	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
18-Sep	C	Flight	Good	Yes	G ex 2	N/A	112	N/A	N/A	41.96%	39.00%	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
18-Sep	C	Flight	Good	Yes	Test set 1	N/A	112	N/A	N/A	41.96%	42.00%	2	100.00%	1.5	12.60	100.00%	3.90	83.33%	2.30	73.00	N/A
18-Sep	C	Flight	Good	Yes	Test set 2	N/A	110	N/A	N/A	40.56%	47.00%	2	100.00%	1.3	11.90	100.00%	4.30	100.00%	1.80	92.00	N/A

Day	Test Subject	Centrifuge /Flight	Data Quality	Bio-feedback	Event	HR Wyle	HR Watch	HR PECGU	%HRR Wyle	%HRR Watch	%HRR PECGU	Borg (0-10)	Code %Accurate	Code Time (s)	Ops Time (s)	Stroop Color %Accurate	Stroop Color Time (s)	Stroop Word %Accurate	Stroop Word Time (s)	Rest Time (s)	Test Score (lower is better)
18-Sep	C	Flight	Good	Yes	Test set 3	N/A	102	N/A	N/A	34.97%	44.00%	3	100.00%	1.6	11.40	100.00%	2.60	100.00%	2.60	93.00	N/A
18-Sep	C	Flight	Good	Yes	Test set 4	N/A	114	N/A	N/A	43.36%	47.00%	3	100.00%	1.3	13.70	100.00%	2.70	100.00%	2.00	N/A	747.64
16-Aug	D	Centrifuge	Good	No	Ground	92.5	N/A	N/A	25.00%	N/A	N/A	0	100.00%	2	14.00	100.00%	4.00	No Data	No Data	N/A	N/A
16-Aug	D	Centrifuge	Good	No	G ex 1	114.55	N/A	N/A	42.50%	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
16-Aug	D	Centrifuge	Good	No	G ex 2	142.9	N/A	N/A	65.00%	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
16-Aug	D	Centrifuge	Good	No	Test set 1	130	N/A	N/A	54.76%	N/A	N/A	5	100.00%	3	9.00	100.00%	5.00	No Data	No Data	70.00	N/A
16-Aug	D	Centrifuge	Good	No	Test set 2	147	N/A	N/A	68.25%	N/A	N/A	7	83.33%	3.6	12.00	100.00%	3.20	No Data	No Data	72.00	N/A
16-Aug	D	Centrifuge	Good	No	Test set 3	160	N/A	N/A	78.57%	N/A	N/A	7	100.00%	2.5	12.30	83.33%	3.80	No Data	No Data	81.00	N/A
16-Aug	D	Centrifuge	Good	No	Test set 4	156	N/A	N/A	75.40%	N/A	N/A	9	83.33%	2.4	13.50	100.00%	4.60	No Data	No Data	N/A	2882.26
15-Aug	D	Centrifuge	Good	Yes	Ground	100	N/A	N/A	30.95%	N/A	N/A	1	100.00%	2	13.00	83.33%	7.00	No Data	No Data	N/A	N/A
15-Aug	D	Centrifuge	Good	Yes	G ex 1	130	N/A	N/A	54.76%	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
15-Aug	D	Centrifuge	Good	Yes	G ex 2	113	N/A	N/A	41.27%	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
15-Aug	D	Centrifuge	Good	Yes	Test set 1	150	N/A	N/A	70.63%	N/A	N/A	5	100.00%	2.3	17.50	100.00%	7.70	No Data	No Data	101.00	N/A
15-Aug	D	Centrifuge	Good	Yes	Test set 2	168	N/A	N/A	84.92%	N/A	N/A	6	80.00%	3	10.80	83.33%	7.00	No Data	No Data	117.00	N/A
15-Aug	D	Centrifuge	Good	Yes	Test set 3	147	N/A	N/A	68.25%	N/A	N/A	7	80.00%	4.3	25.50	100.00%	4.00	No Data	No Data	111.00	N/A
15-Aug	D	Centrifuge	Good	Yes	Test set 4	150	N/A	N/A	70.63%	N/A	N/A	6	100.00%	2	20.40	100.00%	7.60	No Data	No Data	N/A	8998.95
16-Aug	E	Centrifuge	Good	No	Ground	87	N/A	N/A	25.00%	N/A	N/A	0	100.00%	2	12.40	100.00%	3.10	No Data	No Data	0.00	N/A
16-Aug	E	Centrifuge	Good	No	G ex 1	112.9	N/A	N/A	42.50%	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
16-Aug	E	Centrifuge	Good	No	G ex 2	127.7	N/A	N/A	52.50%	N/A	N/A	2	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
16-Aug	E	Centrifuge	Good	No	Test set 1	138.8	N/A	N/A	60.00%	N/A	N/A	4	20.00%	1.9	14.90	83.33%	9.00	No Data	No Data	97.00	N/A
16-Aug	E	Centrifuge	Good	No	Test set 2	155	N/A	N/A	70.95%	N/A	N/A	6	20.00%	1.9	16.21	83.33%	2.60	No Data	No Data	122.00	N/A
16-Aug	E	Centrifuge	Good	No	Test set 3	157.3	N/A	N/A	72.50%	N/A	N/A	7	20.00%	2.2	13.10	100.00%	3.00	No Data	No Data	89.00	N/A
16-Aug	E	Centrifuge	Good	No	Test set 4	160	N/A	N/A	74.32%	N/A	N/A	7	20.00%	3.8	15.40	100.00%	3.70	No Data	No Data		11674.5
15-Aug	E	Centrifuge	Good	Yes	Ground	83.3	No Data	87	22.50%	No Data	25.00%	0	100.00%	2	4.10	100.00%	4.40	No Data	No Data	0.00	N/A
15-Aug	E	Centrifuge	Good	Yes	G ex 1	90.7	No Data	93	27.50%	No Data	29.05%	1	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
15-Aug	E	Centrifuge	Good	Yes	G ex 2	116.6	No Data	127	45.00%	No Data	52.03%	2	N/A	N/A	N/A	N/A	N/A	No Data	No Data	N/A	N/A
15-Aug	E	Centrifuge	Good	Yes	Test set 1	155	No Data	N/A	70.95%	No Data	N/A	5	40.00%	4.3	9.00	100.00%	5.90	No Data	No Data	102.00	N/A

Day	Test Subject	Centrifuge /Flight	Data Quality	Bio-feedback	Event	HR Wyle	HR Watch	HR PECGU	%HRR Wyle	%HRR Watch	%HRR PECGU	Borg (0-10)	Code %Accurate	Code Time (s)	Ops Time (s)	Stroop Color %Accurate	Stroop Color Time (s)	Stroop Word %Accurate	Stroop Word Time (s)	Rest Time (s)	Test Score (lower is better)
15-Aug	E	Centrifuge	Good	Yes	Test set 2	170	No Data	N/A	81.08 %	No Data	N/A	8	60.00 %	1	8.80	100.00%	2.40	No Data	No Data	230.00	N/A
15-Aug	E	Centrifuge	Good	Yes	Test set 3	175	No Data	N/A	84.46 %	No Data	N/A	8	40.00 %	4.9	6.10	100.00%	4.40	No Data	No Data	274.00	N/A
15-Aug	E	Centrifuge	Good	Yes	Test set 4	172	No Data	N/A	82.43 %	No Data	N/A	8	20.00 %	N/A	7.70	100.00%	6.80	No Data	No Data		34393.57

Figure 47: Phase 3 and 4 Master Data Spreadsheet

Appendix C – Subject A-E VO_{2max} Results

****Subject A VO_{2max} graph unavailable due to errors in data****

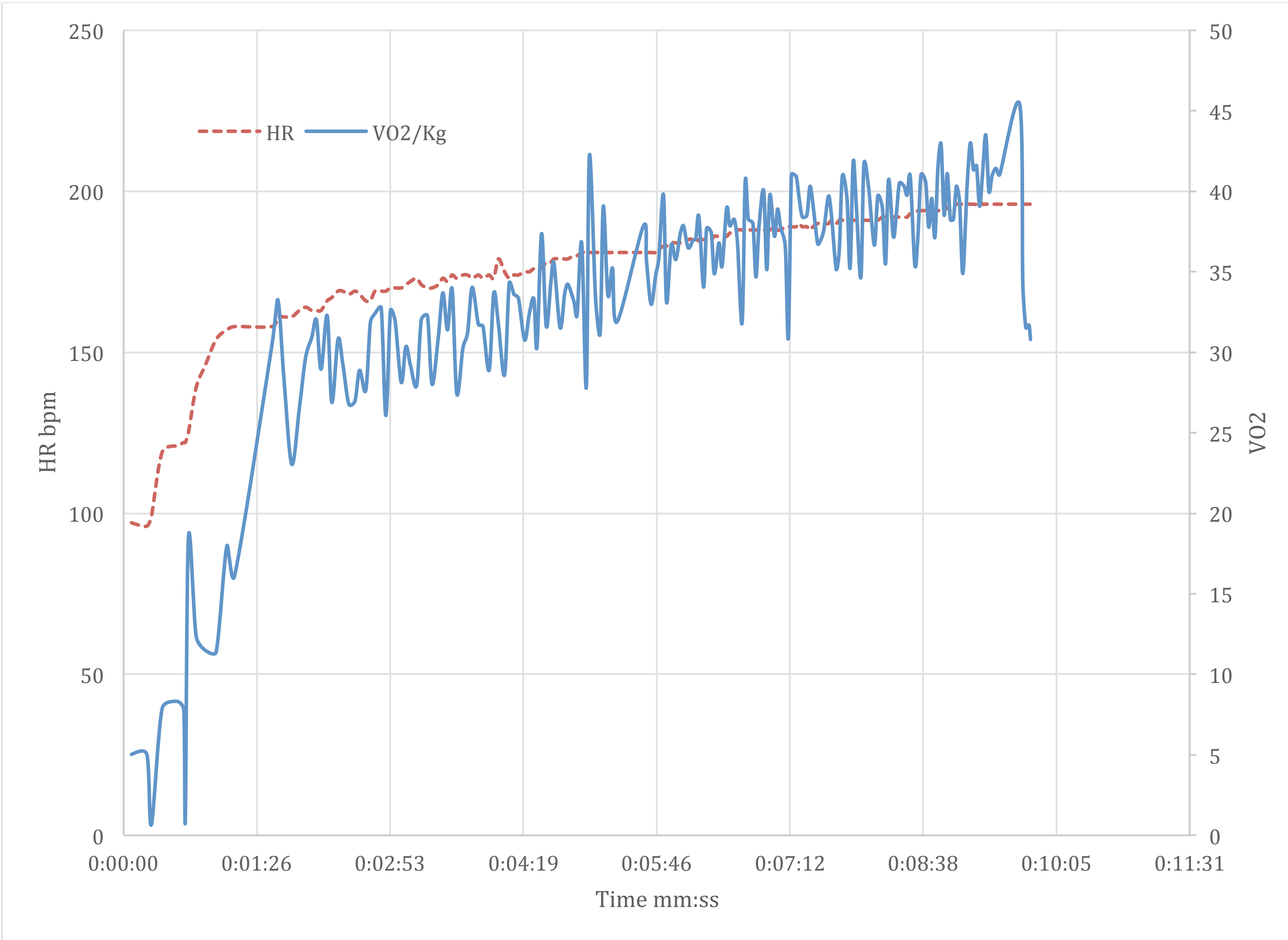


Figure 48: Subject B VO_{2max}

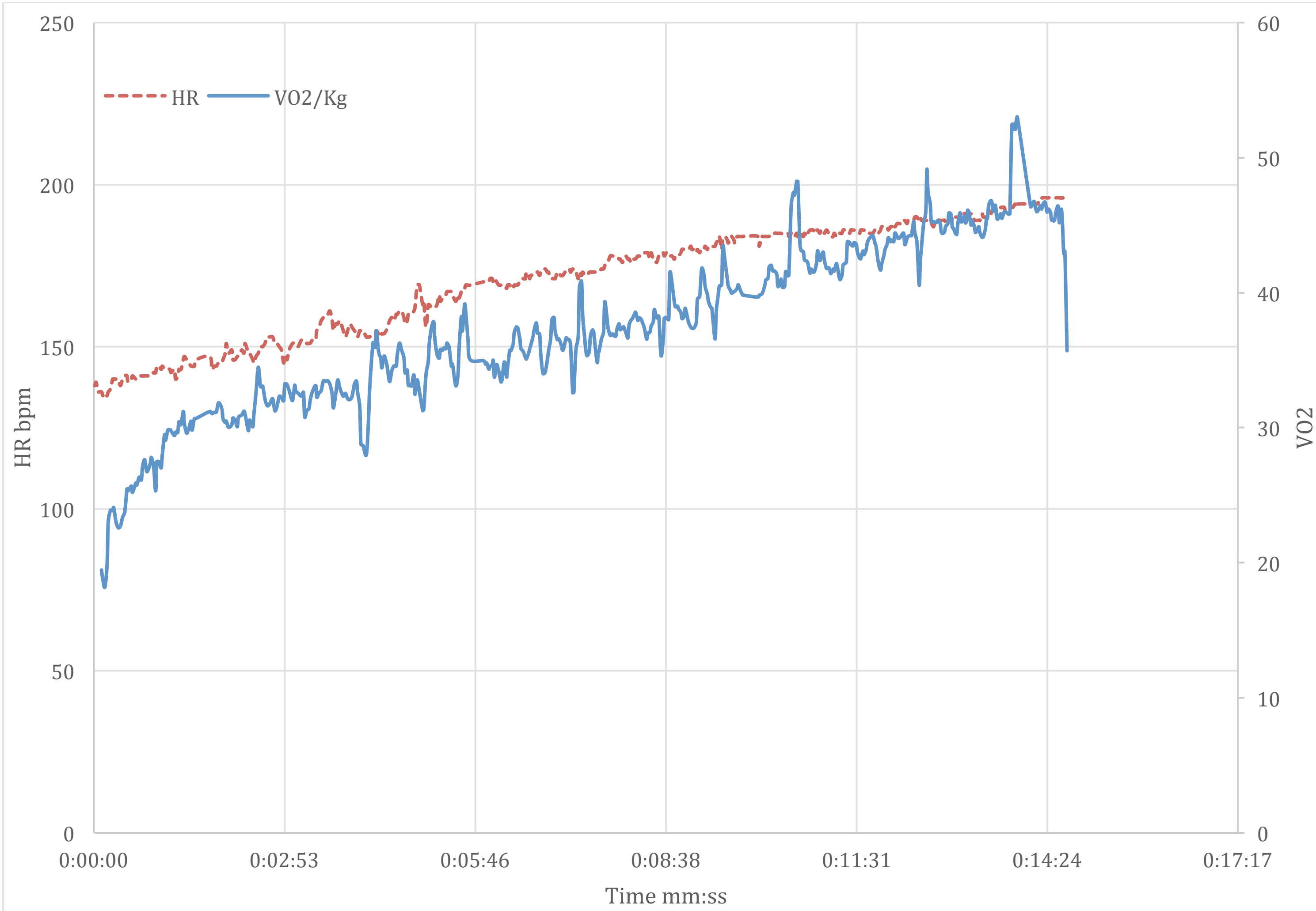


Figure 49 Subject C VO_{2max}

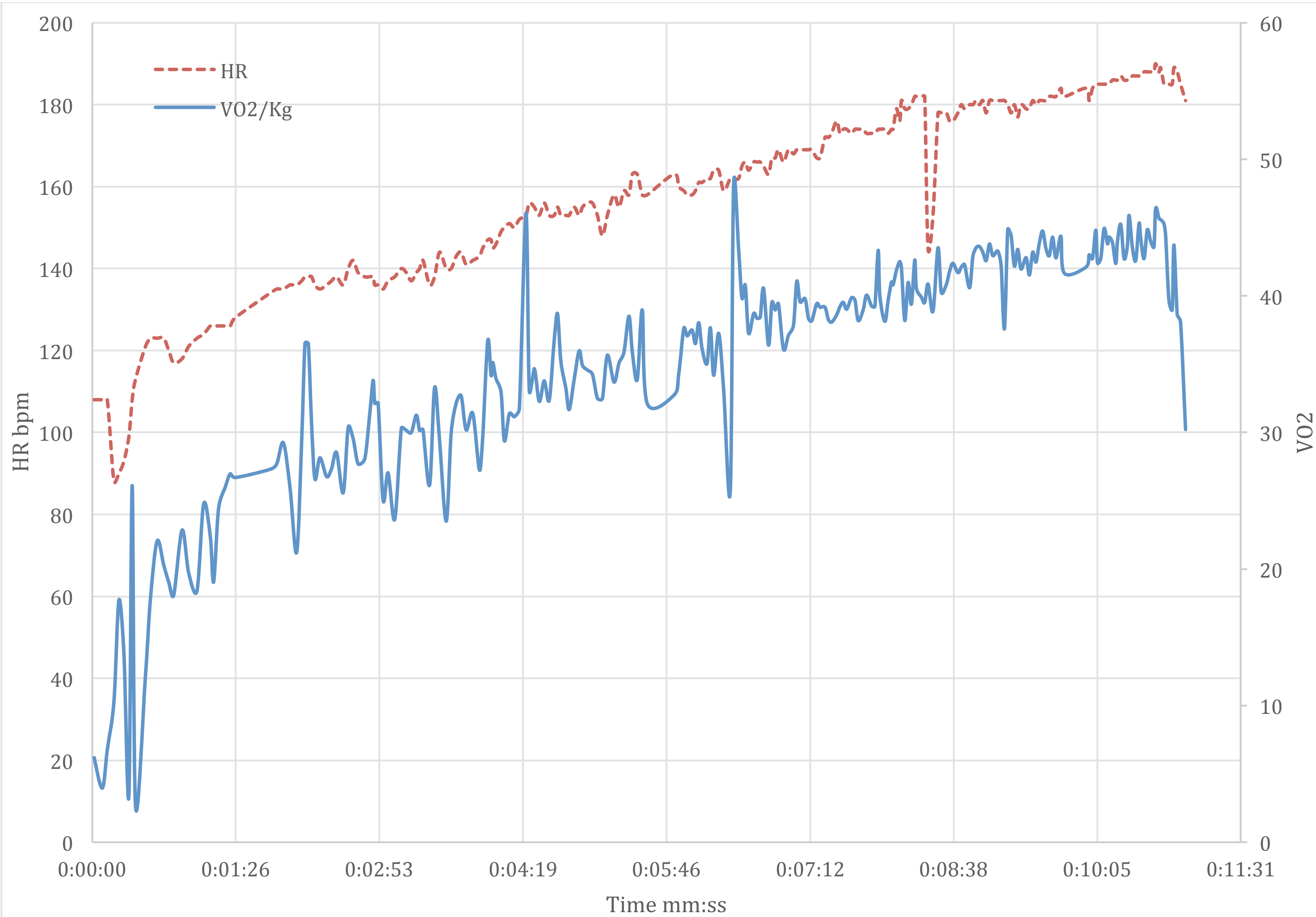


Figure 50: Subject D VO_{2max}

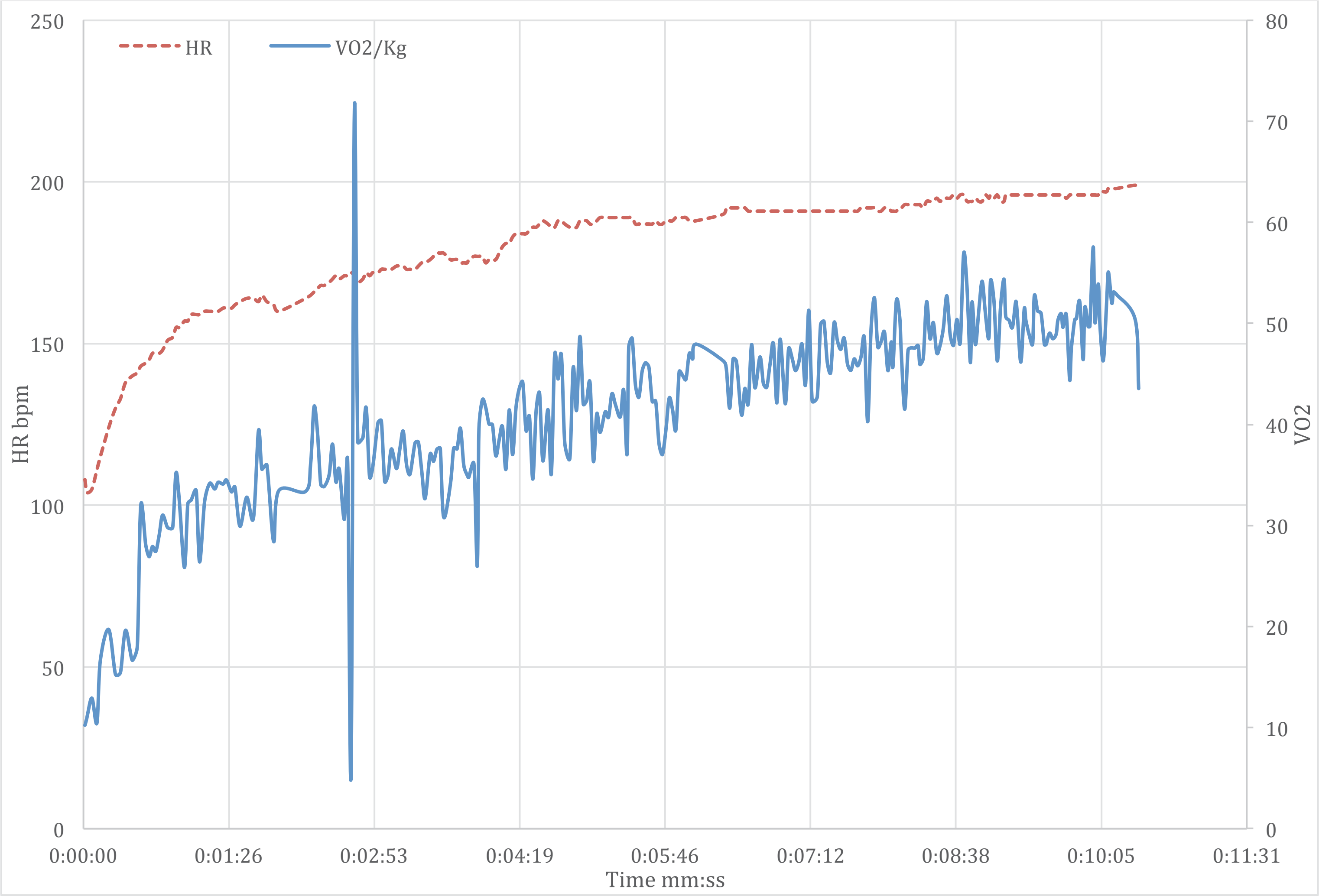
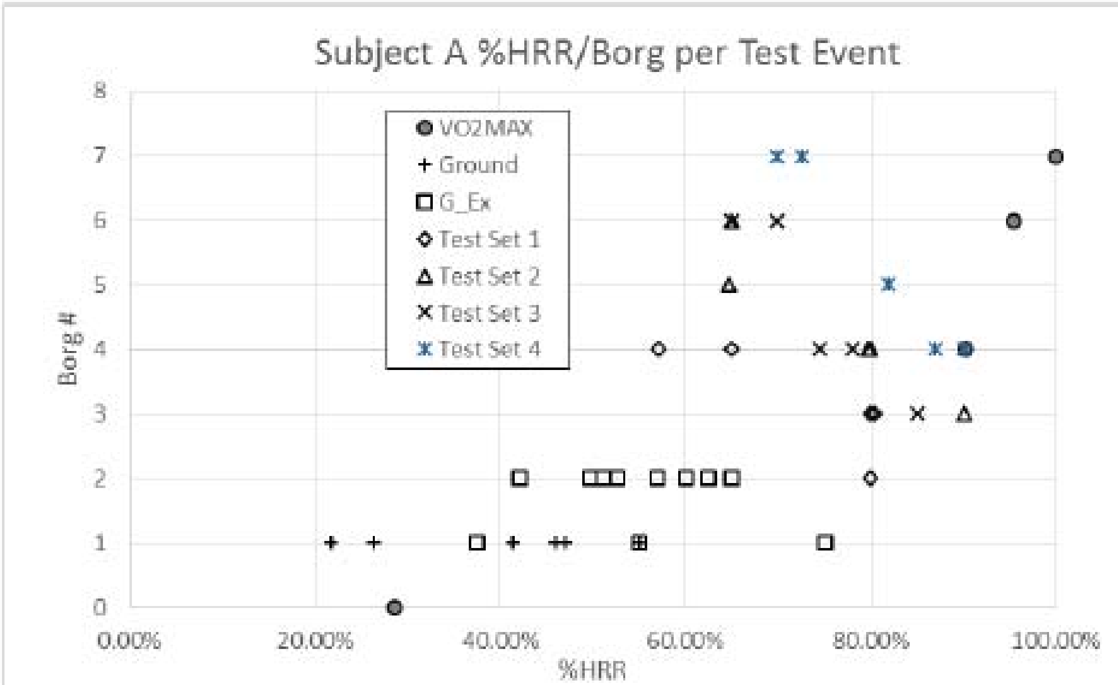


Figure 51: Subject E VO_{2max}

Appendix D – Subject A-E Physiological and Cognitive Results



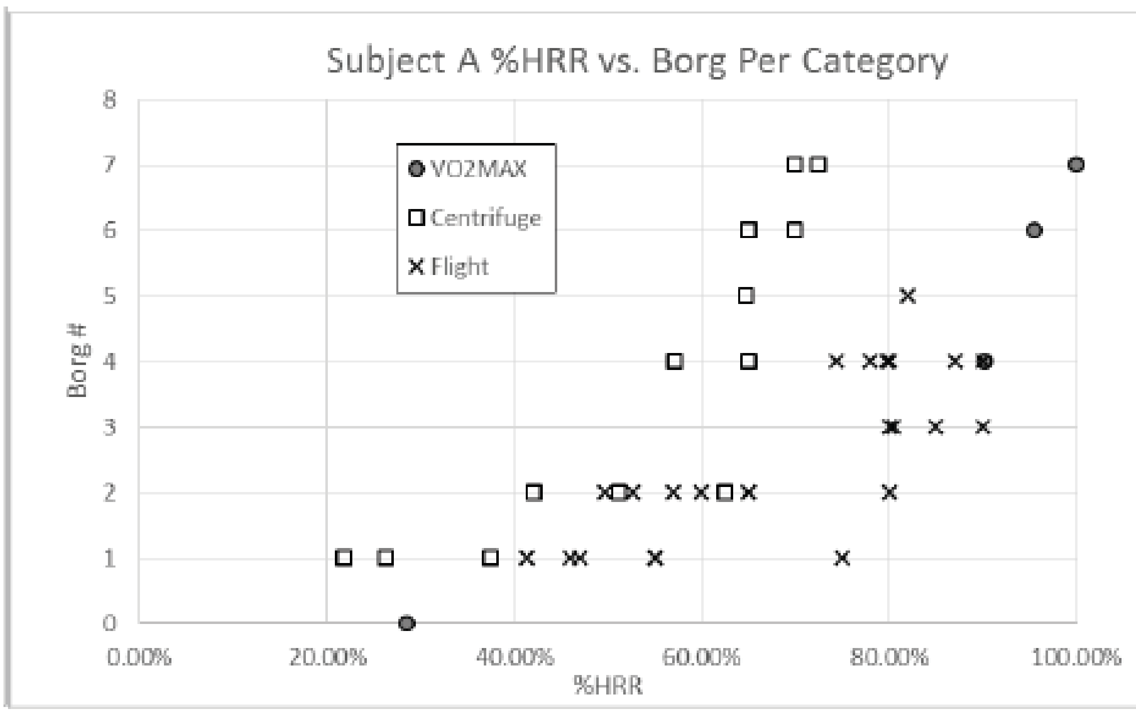


Figure 52: Subject A %HRR vs. Borg RPE Score (by Test Event and Category)

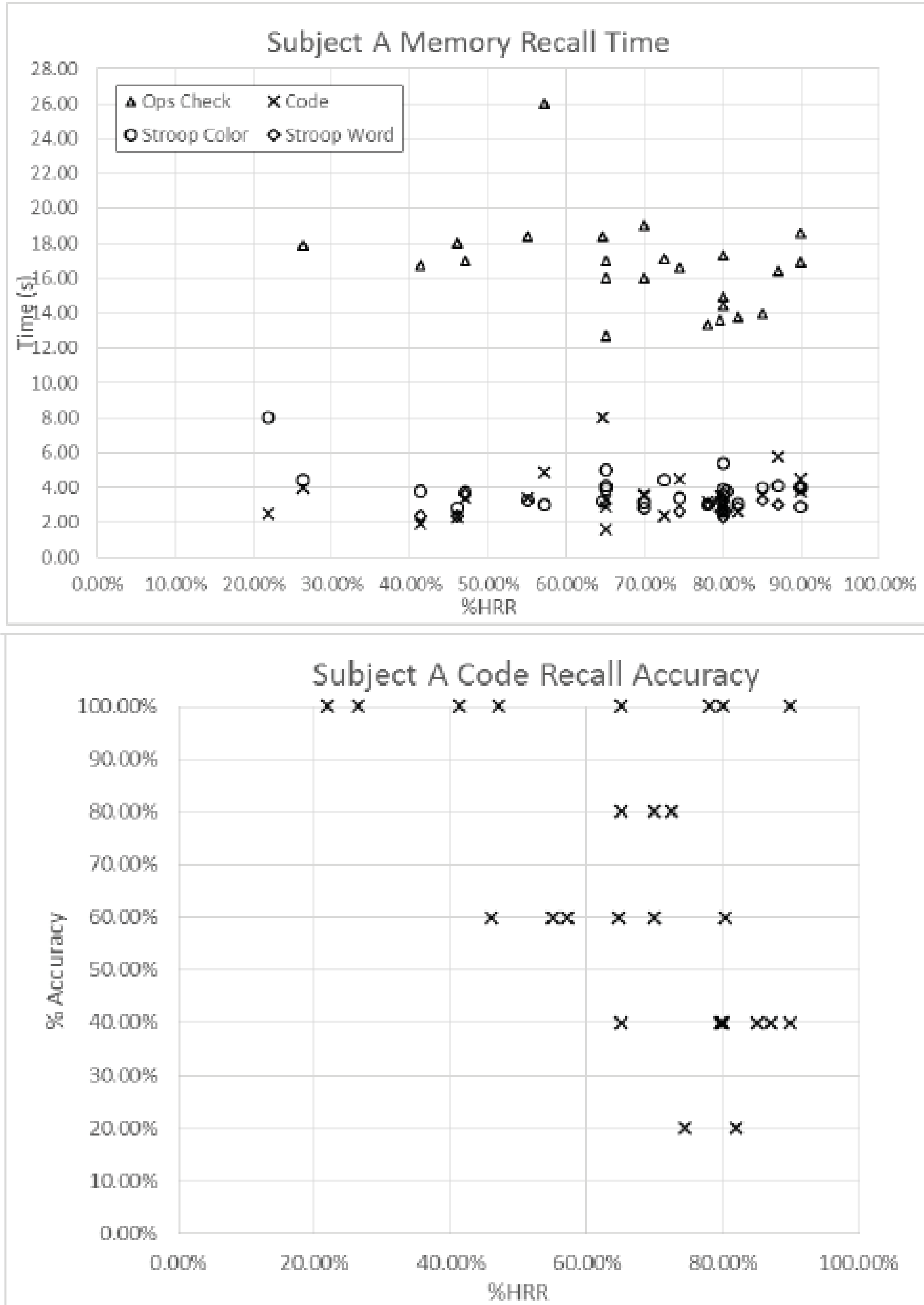
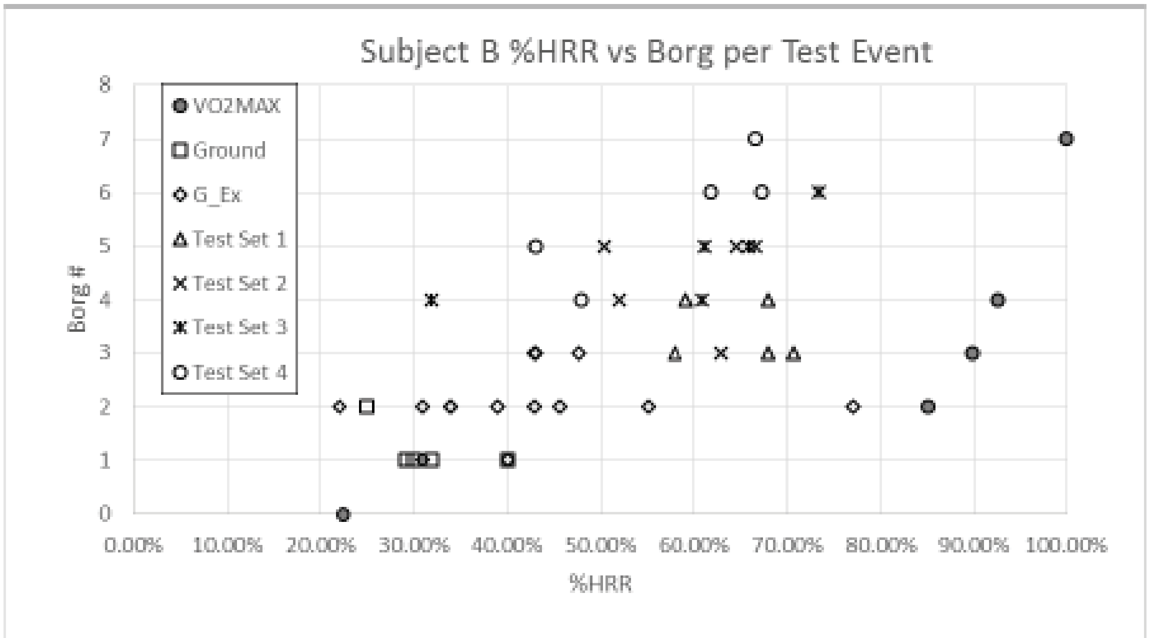


Figure 53: Subject A Cognitive Results (Time and Accuracy)



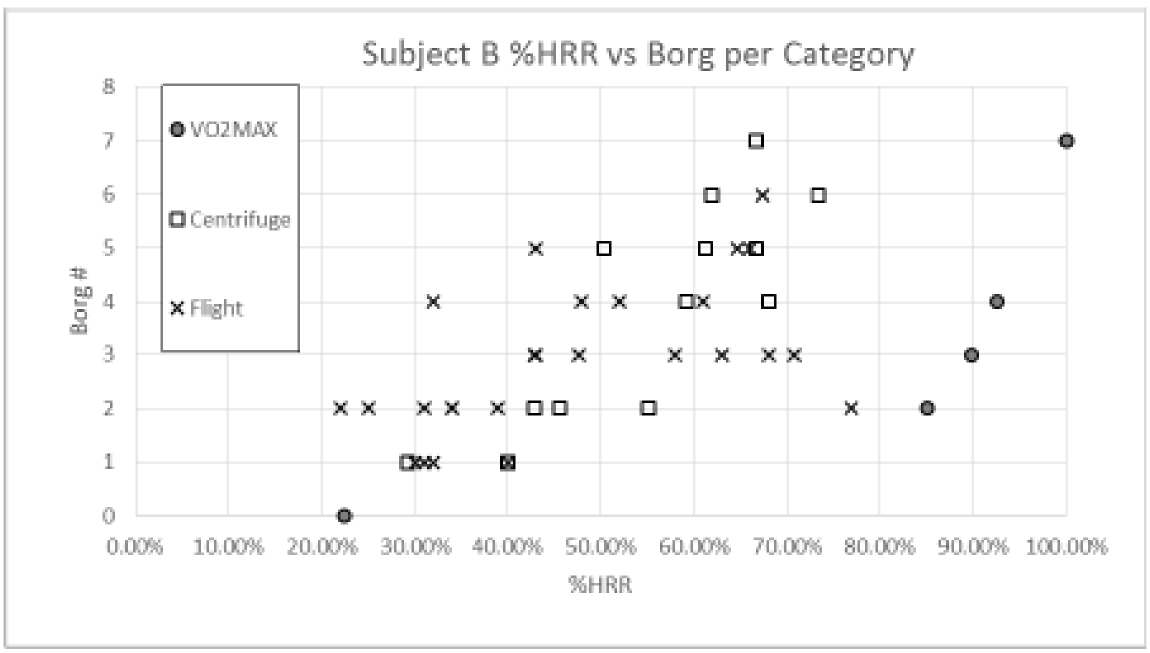
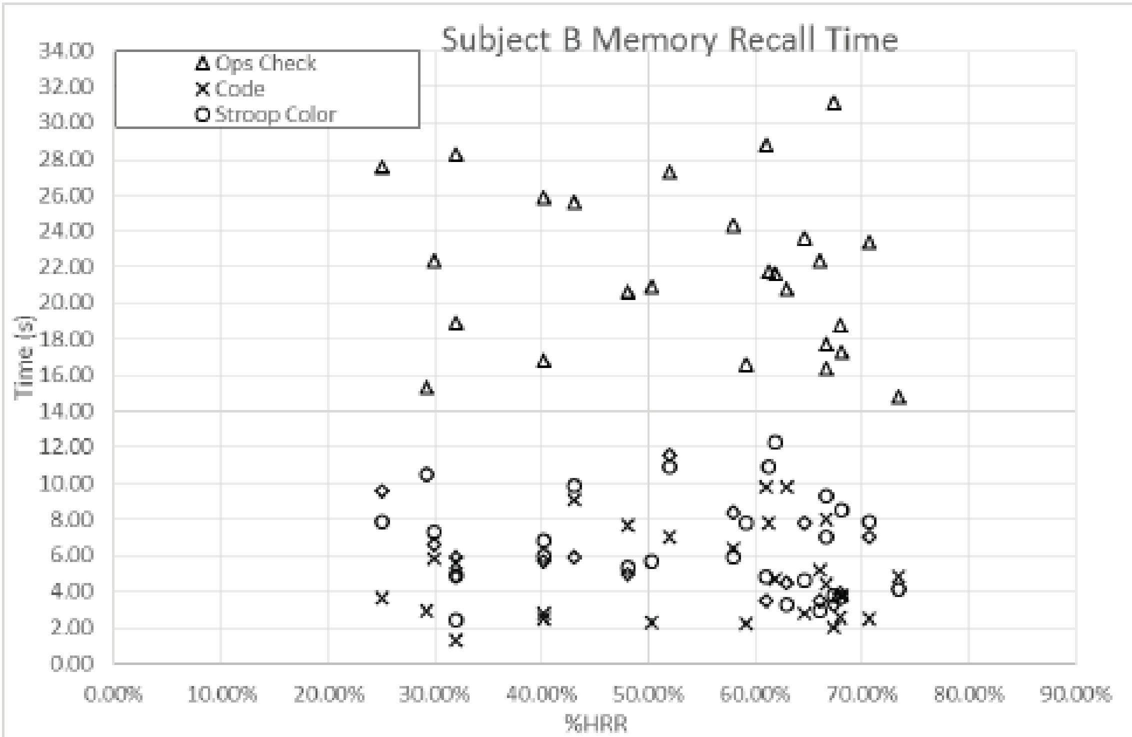


Figure 54: Subject B %HRR vs. Borg RPE Score (by Test Event and Category)



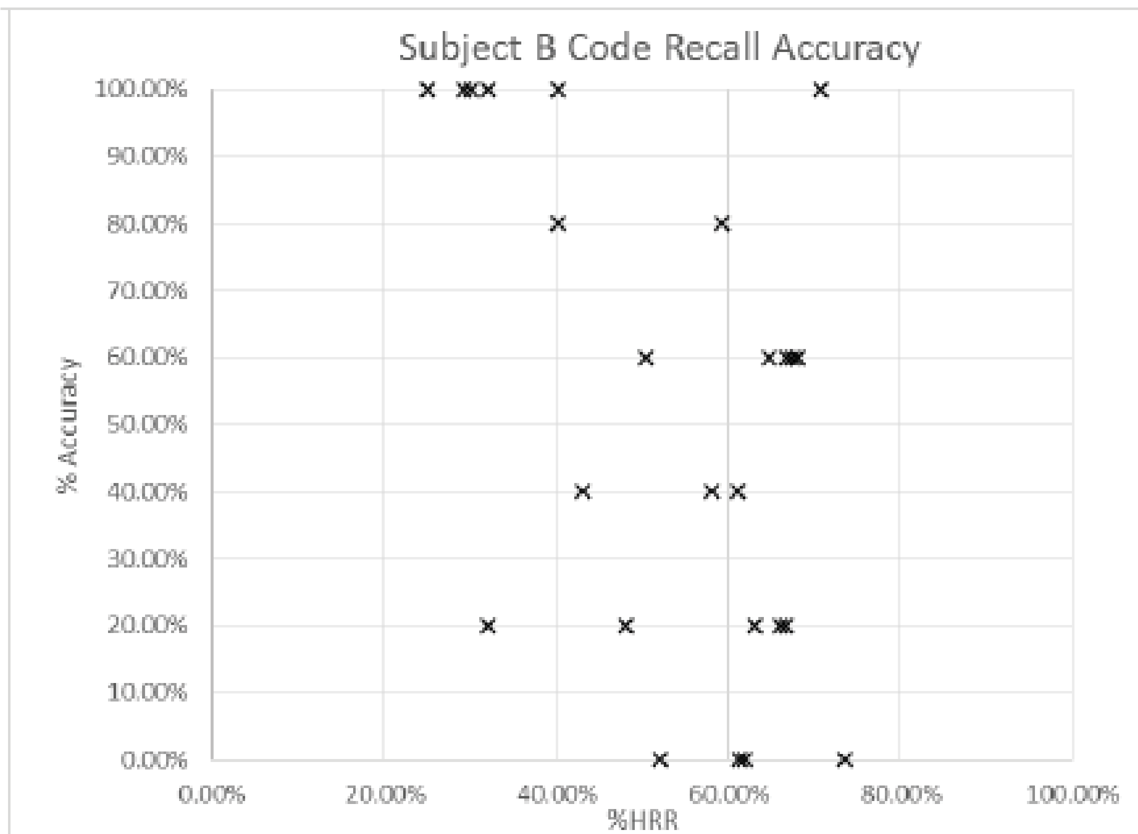
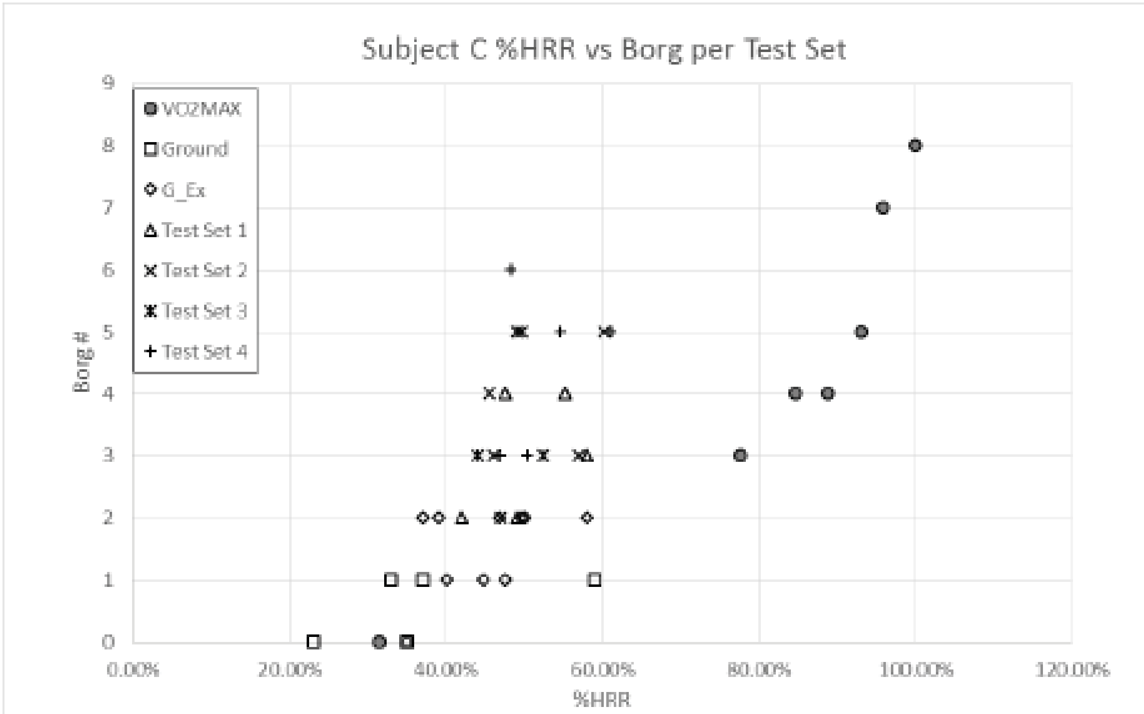


Figure 55: Subject B Cognitive Results (Time and Accuracy)



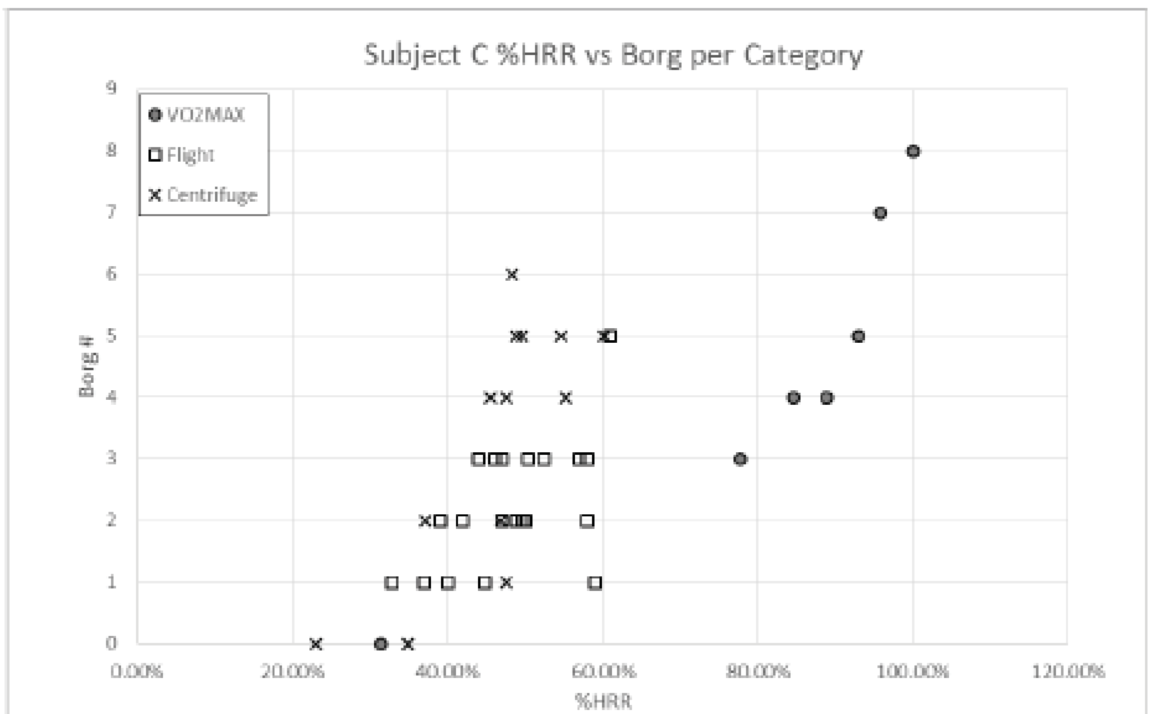


Figure 56: Subject C %HRR vs. Borg RPE Score (by Test Event and Category)

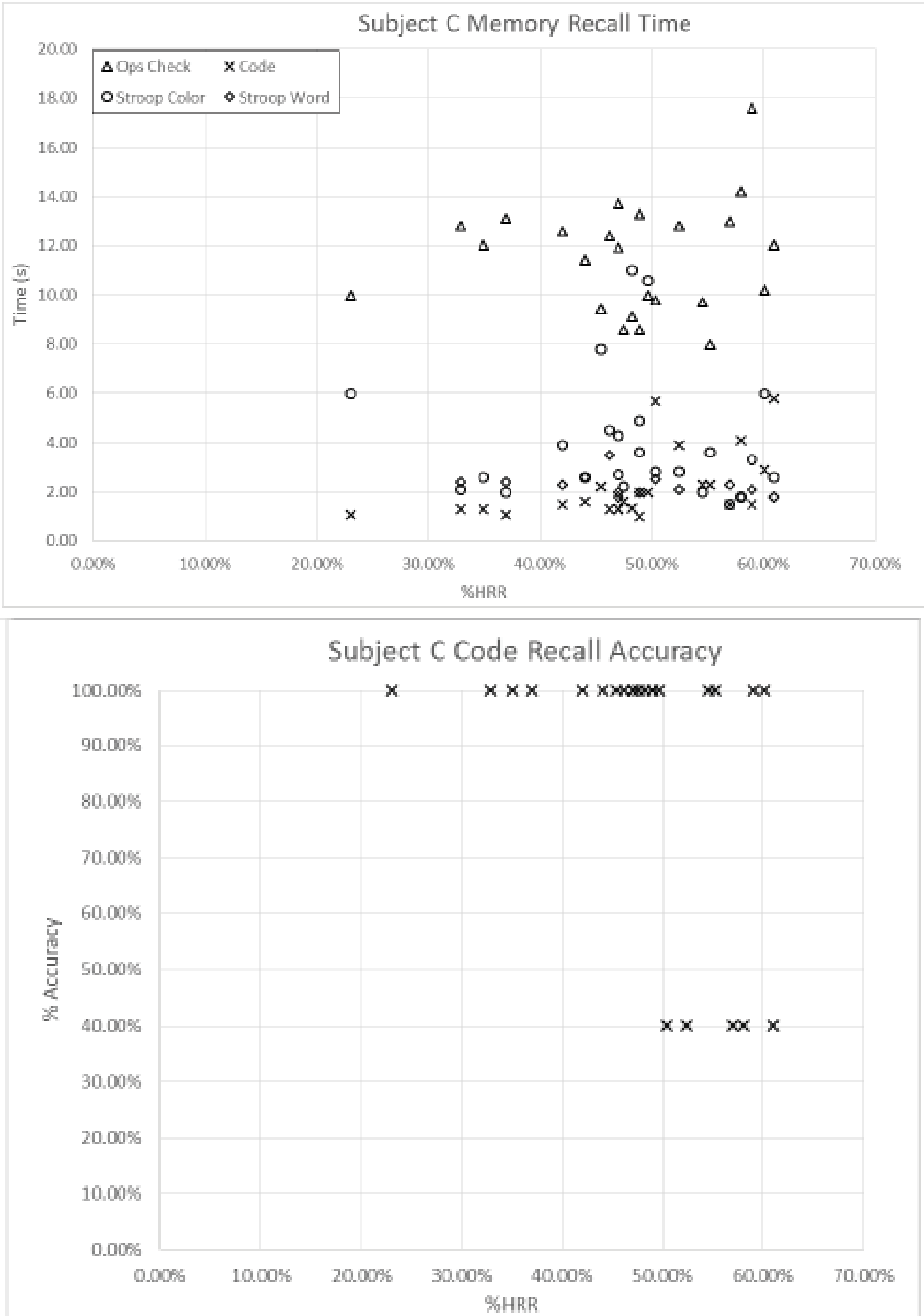


Figure 57: Subject C Cognitive Results (Time and Accuracy)

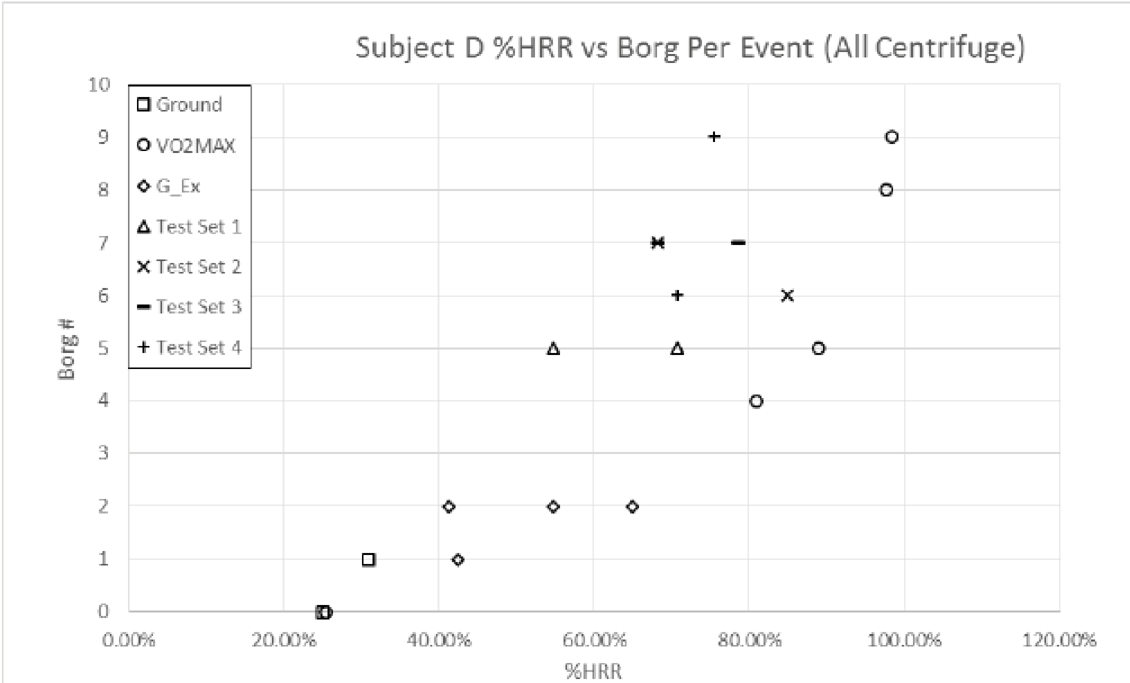
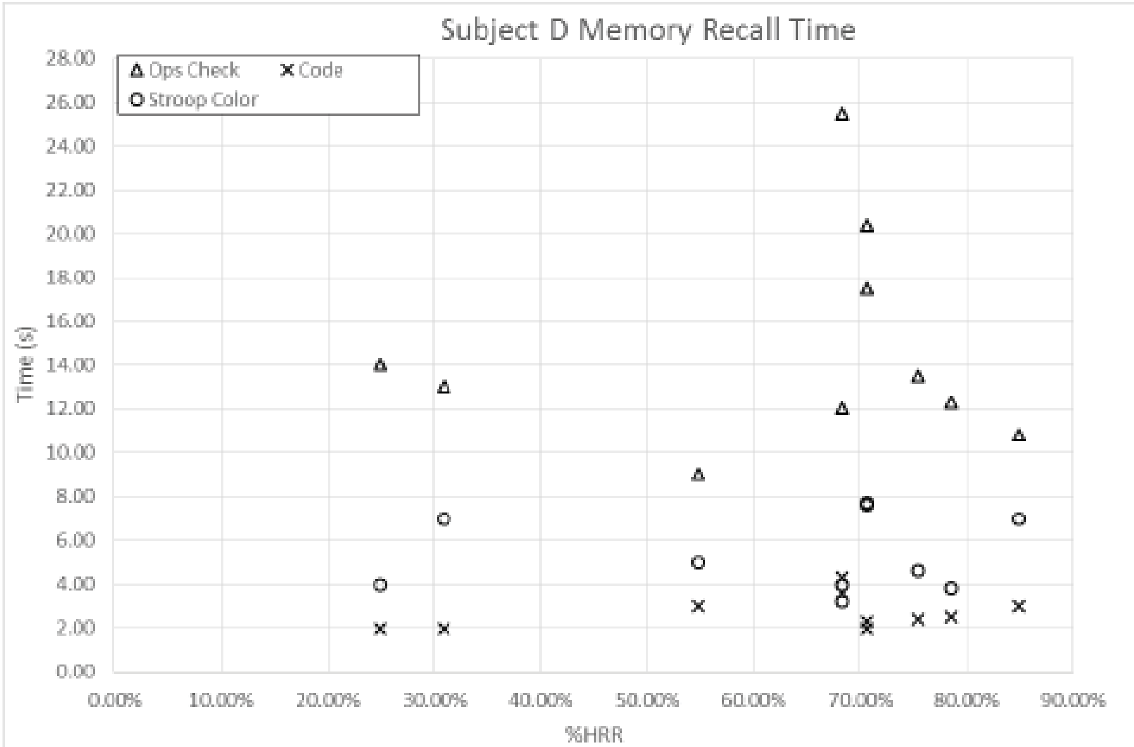


Figure 58: Subject D %HRR vs. Borg RPE Score (by Test Event - All Centrifuge)



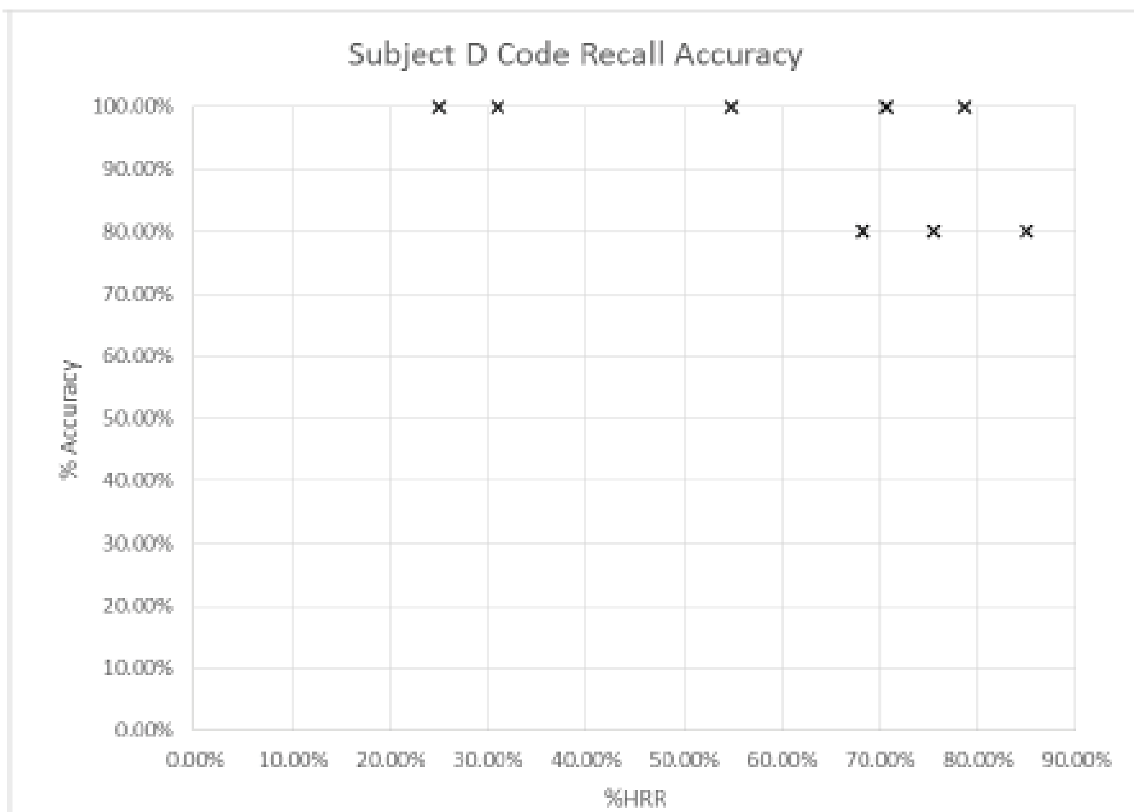


Figure 59: Subject D Cognitive Results (Time and Accuracy)

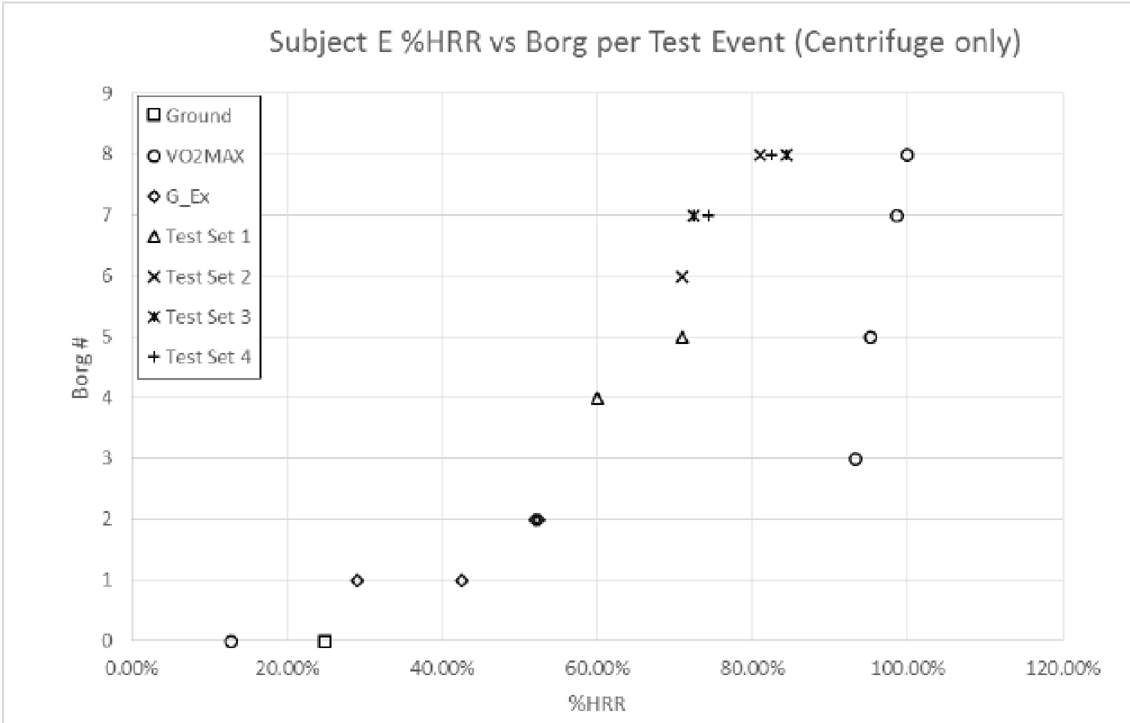
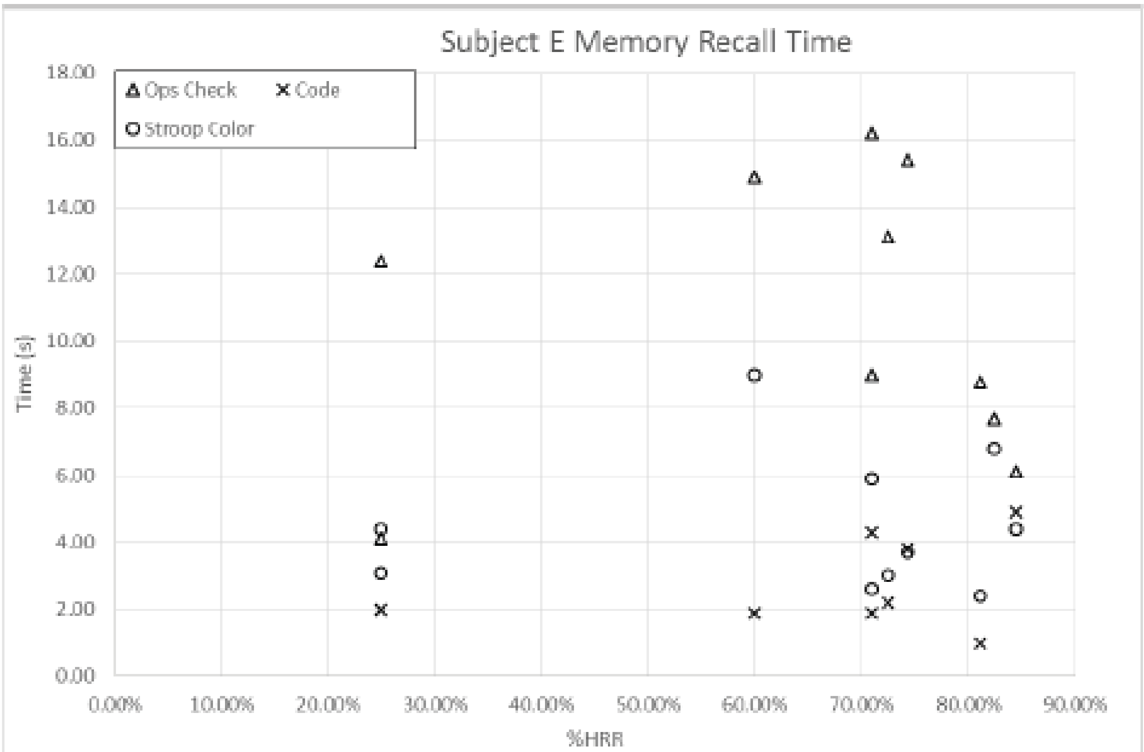


Figure 60: Subject E %HRR vs. Borg RPE Score (by Test Event - All Centrifuge)



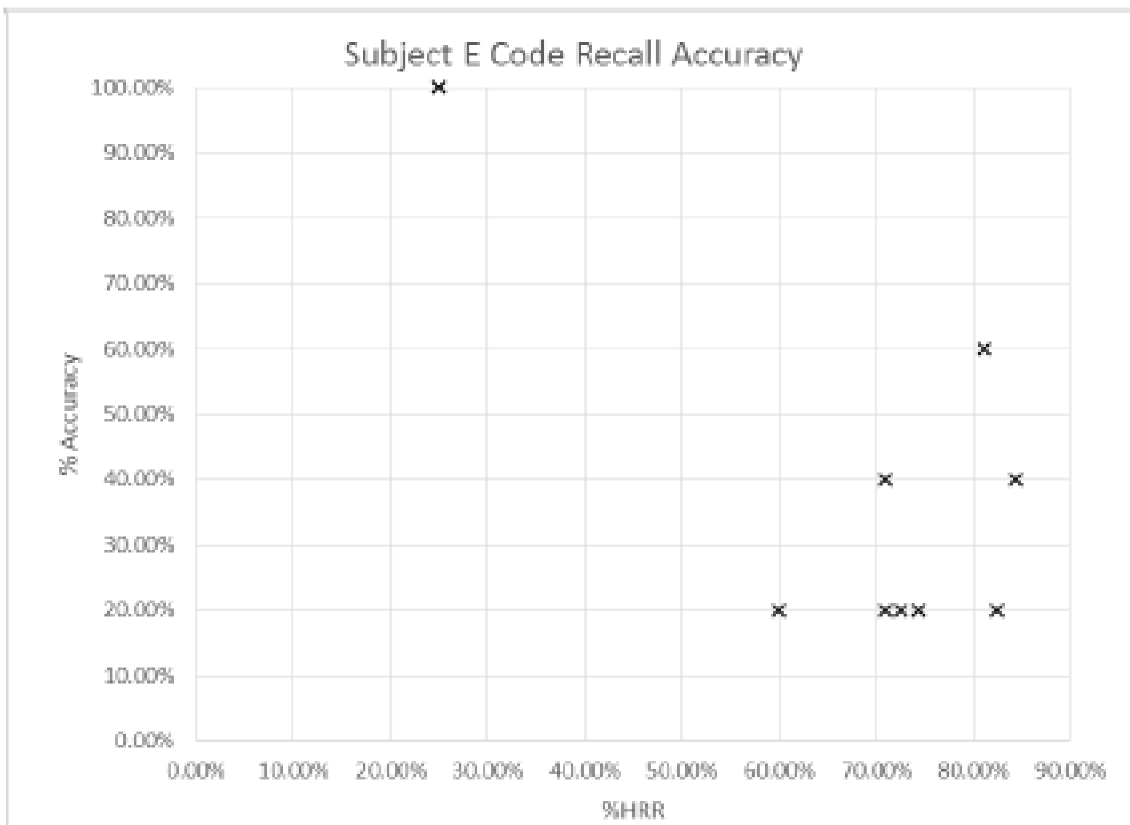


Figure 61: Subject E Cognitive Results (Time and Accuracy)

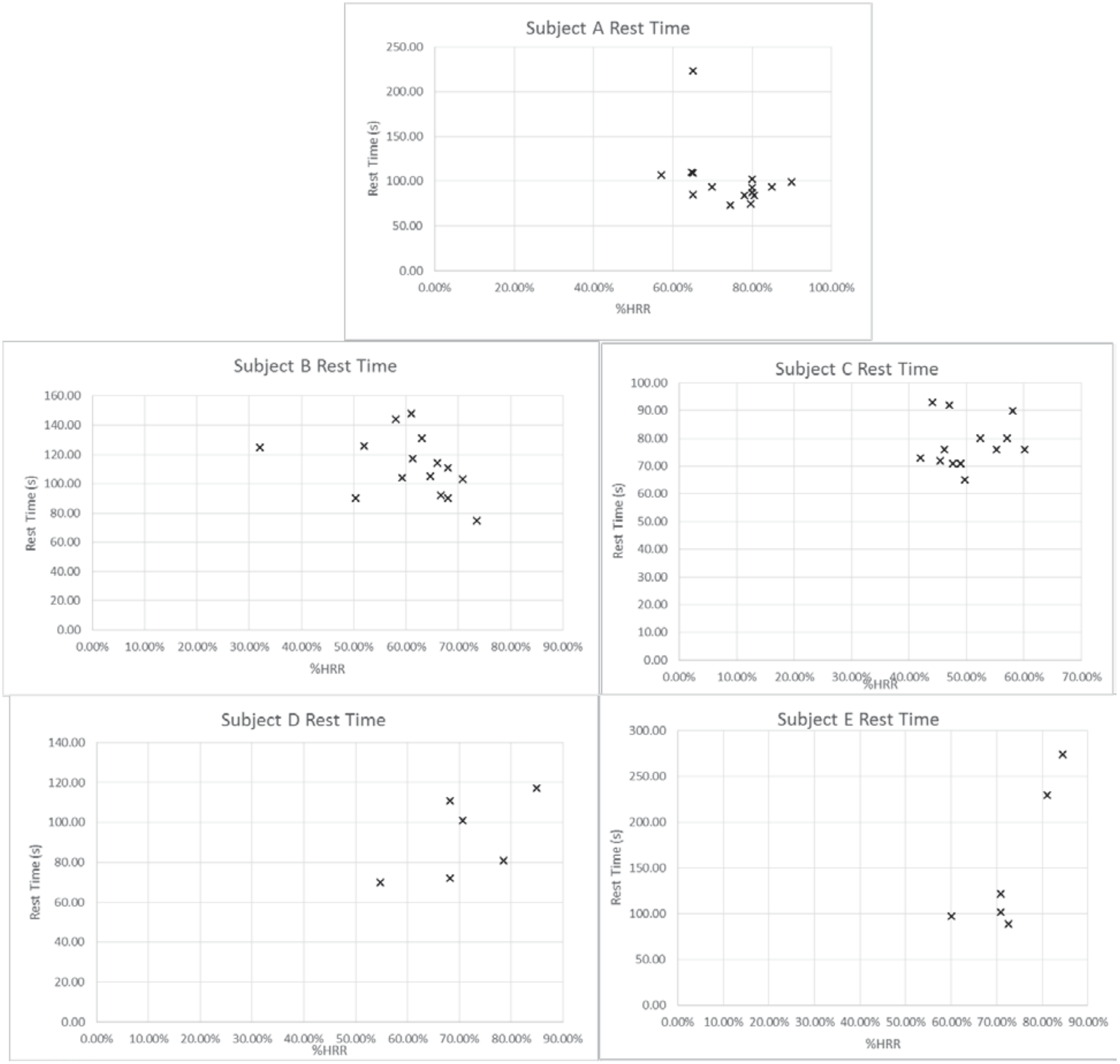


Figure 62: Subject A-E Rest Times (%HRR When Rest Began)

Appendix E – Subject A-E Phase 3 %HRR vs. G

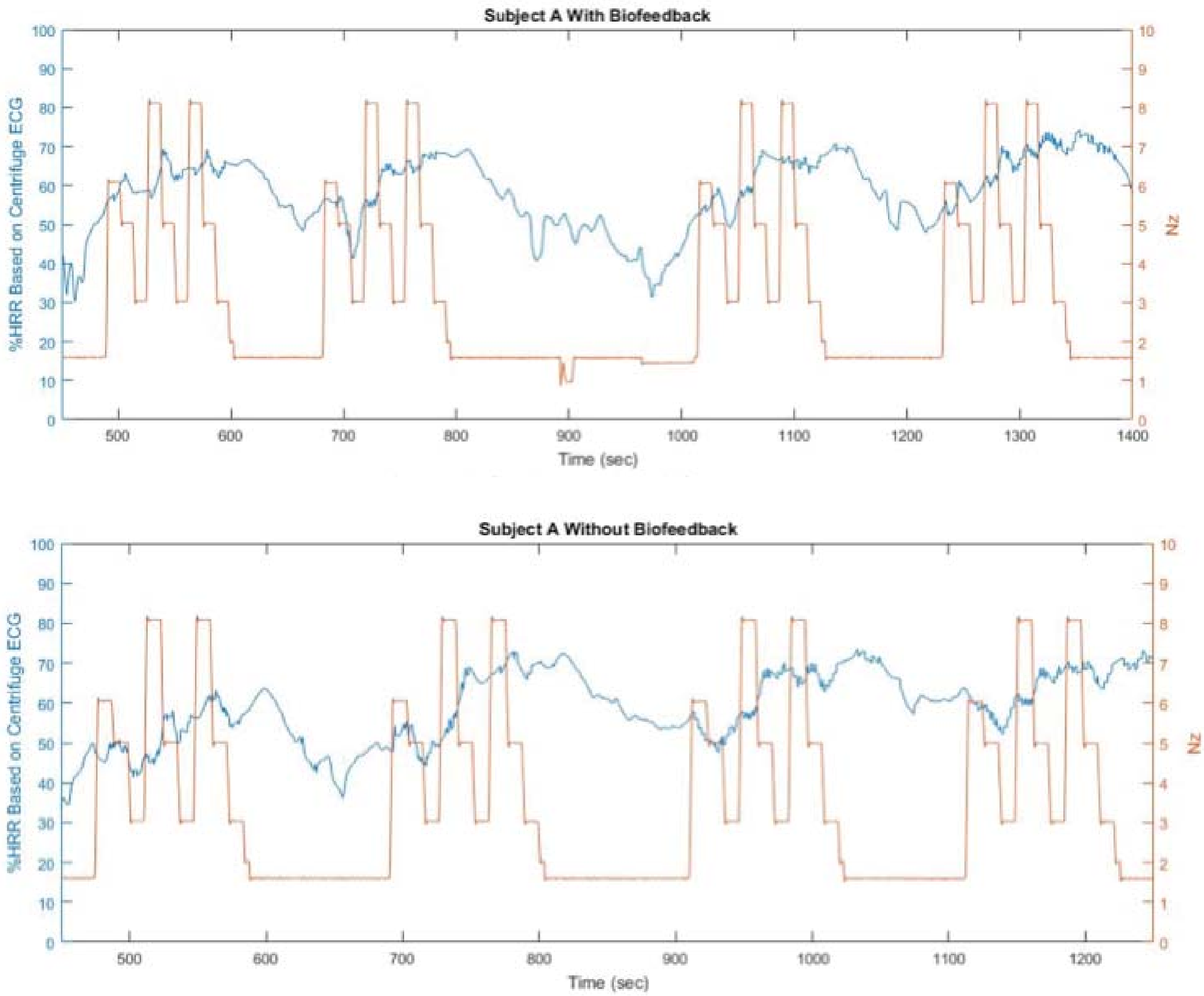


Figure 63: Subject A Phase 3 %HRR vs. G

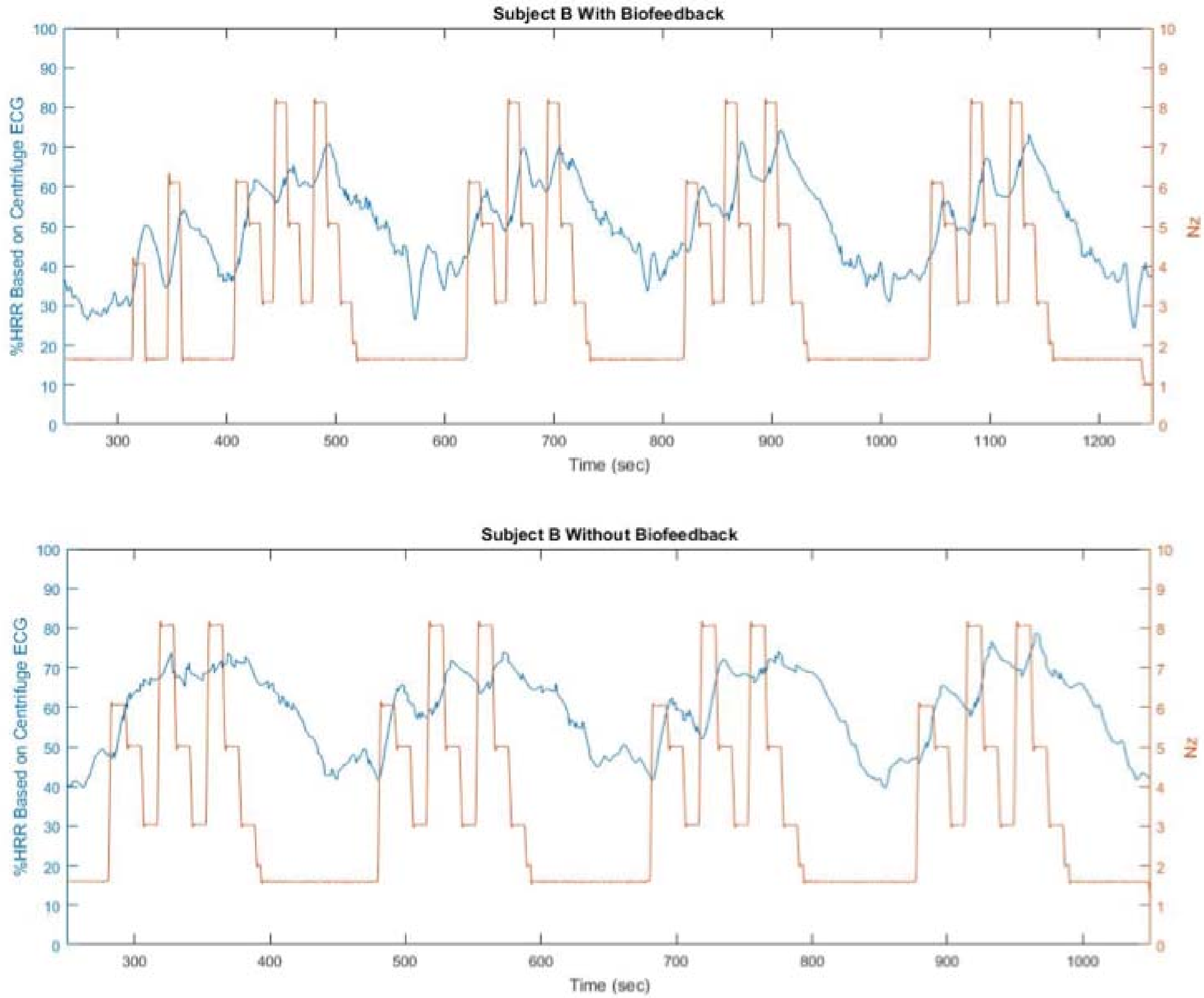


Figure 64: Subject B Phase 3 %HRR vs. G

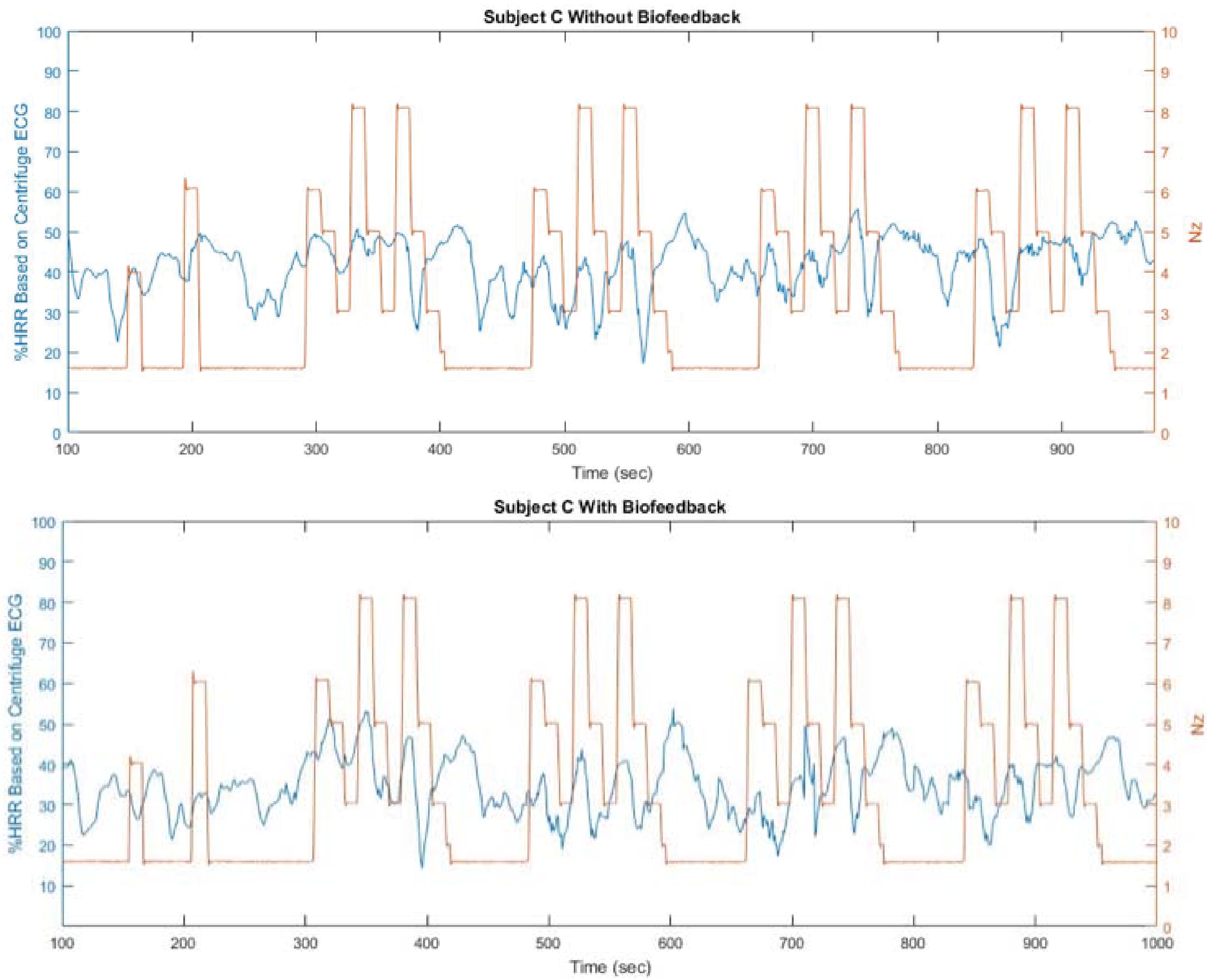


Figure 65: Subject C Phase 3 %HRR vs. G

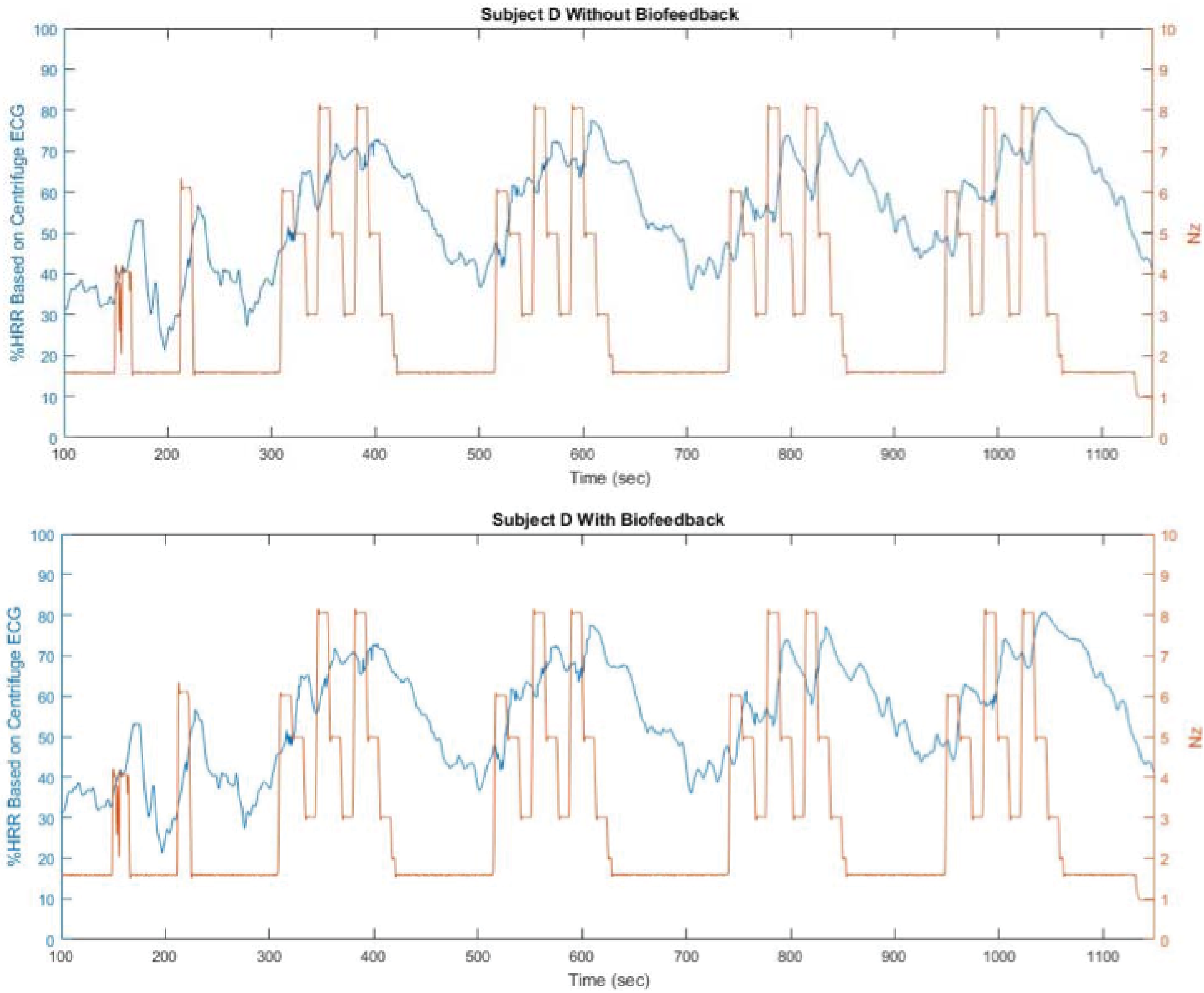


Figure 66: Subject D Phase 3 %HRR vs. G

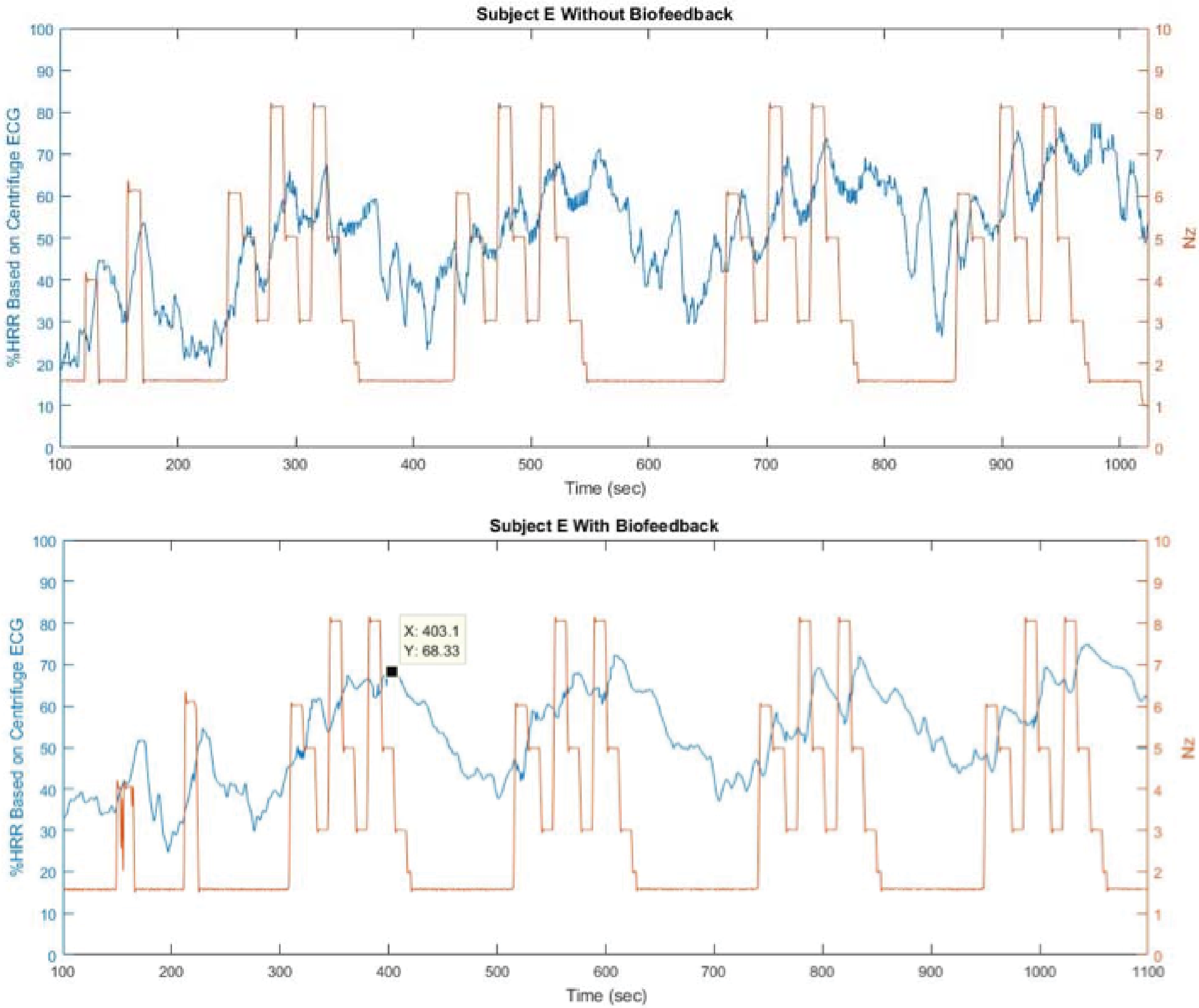
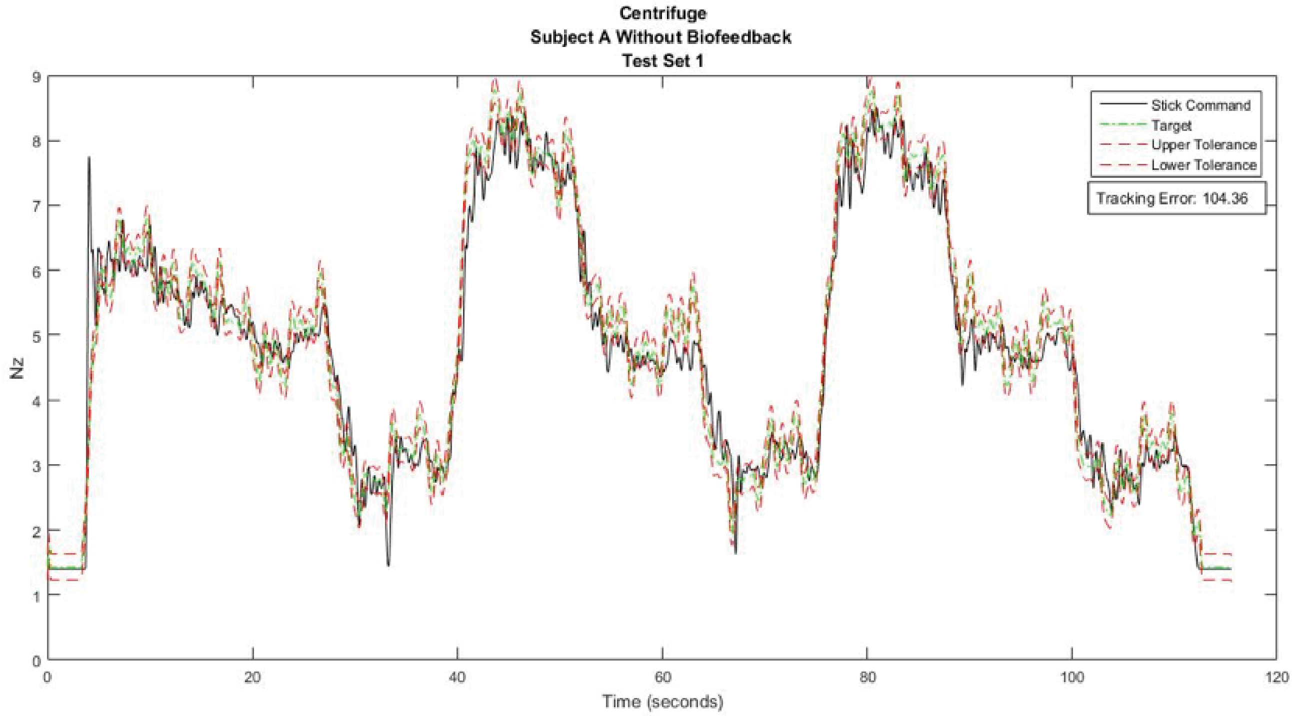


Figure 67: Subject E Phase 3 %HRR vs. G

Appendix F – Subject A-E Phase 3 G-Tracking Scores



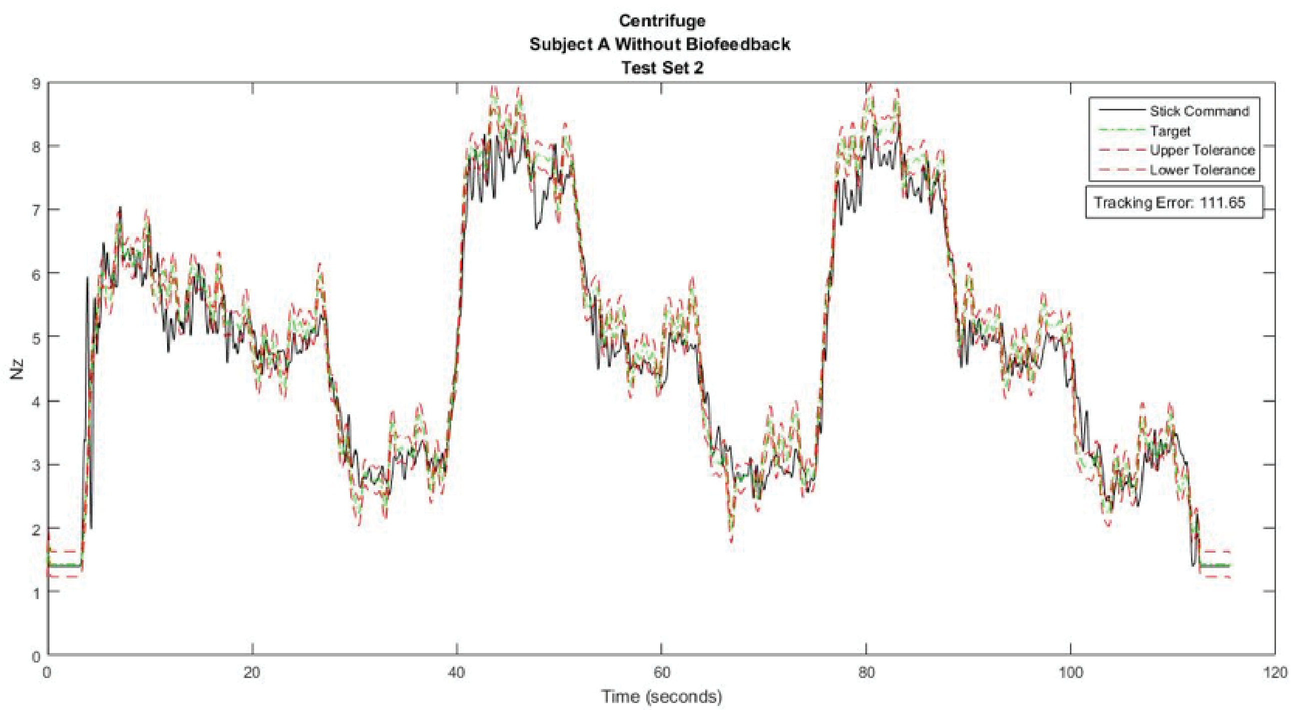
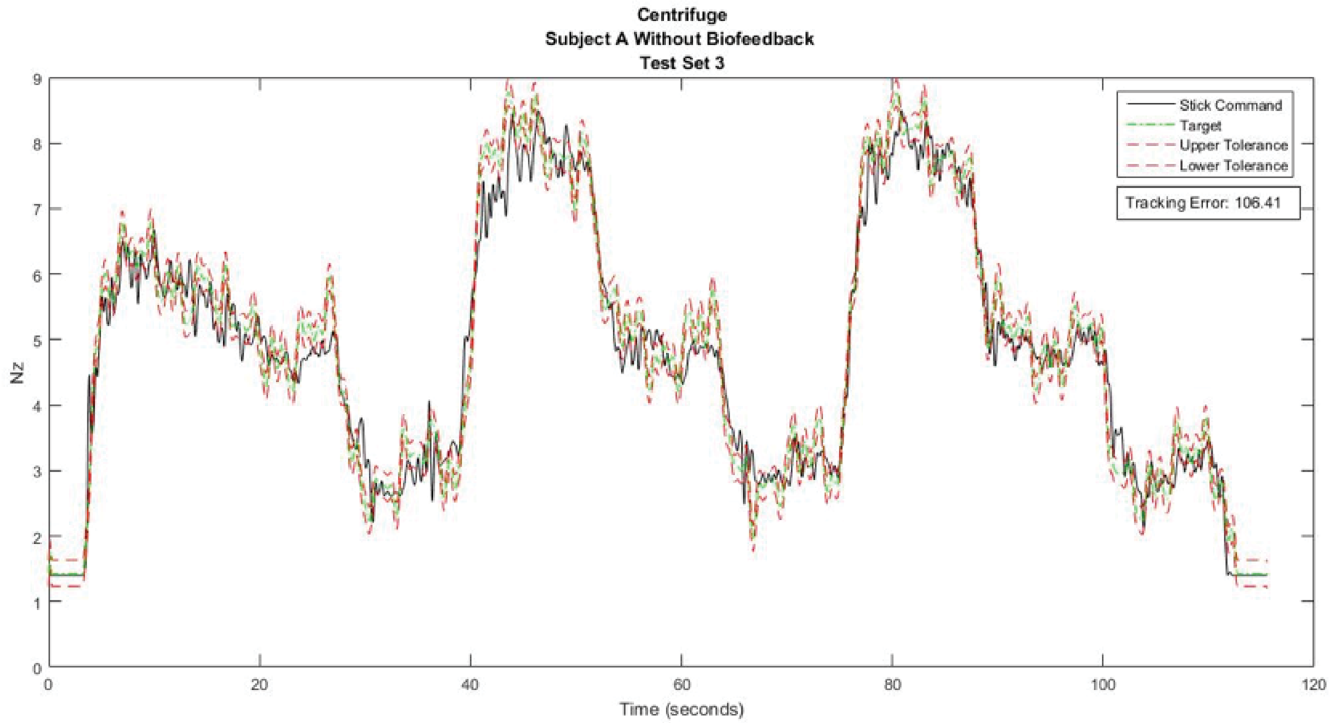


Figure 68: Subject A Phase 3 Without Biofeedback Test Sets 1-2



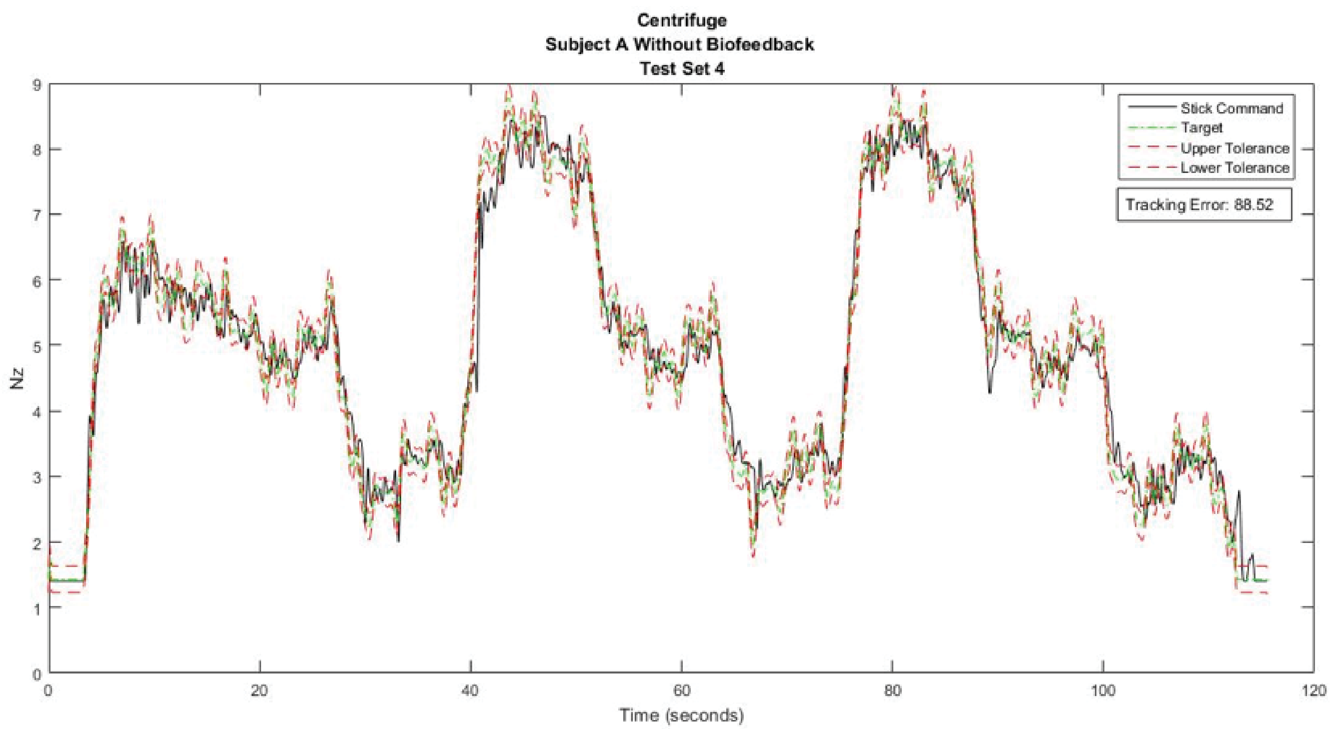


Figure 69: Subject A Phase 3 Without Biofeedback Test Sets 3-4

****Subject A Phase 3 With Biofeedback Test Sets unavailable due to data errors****

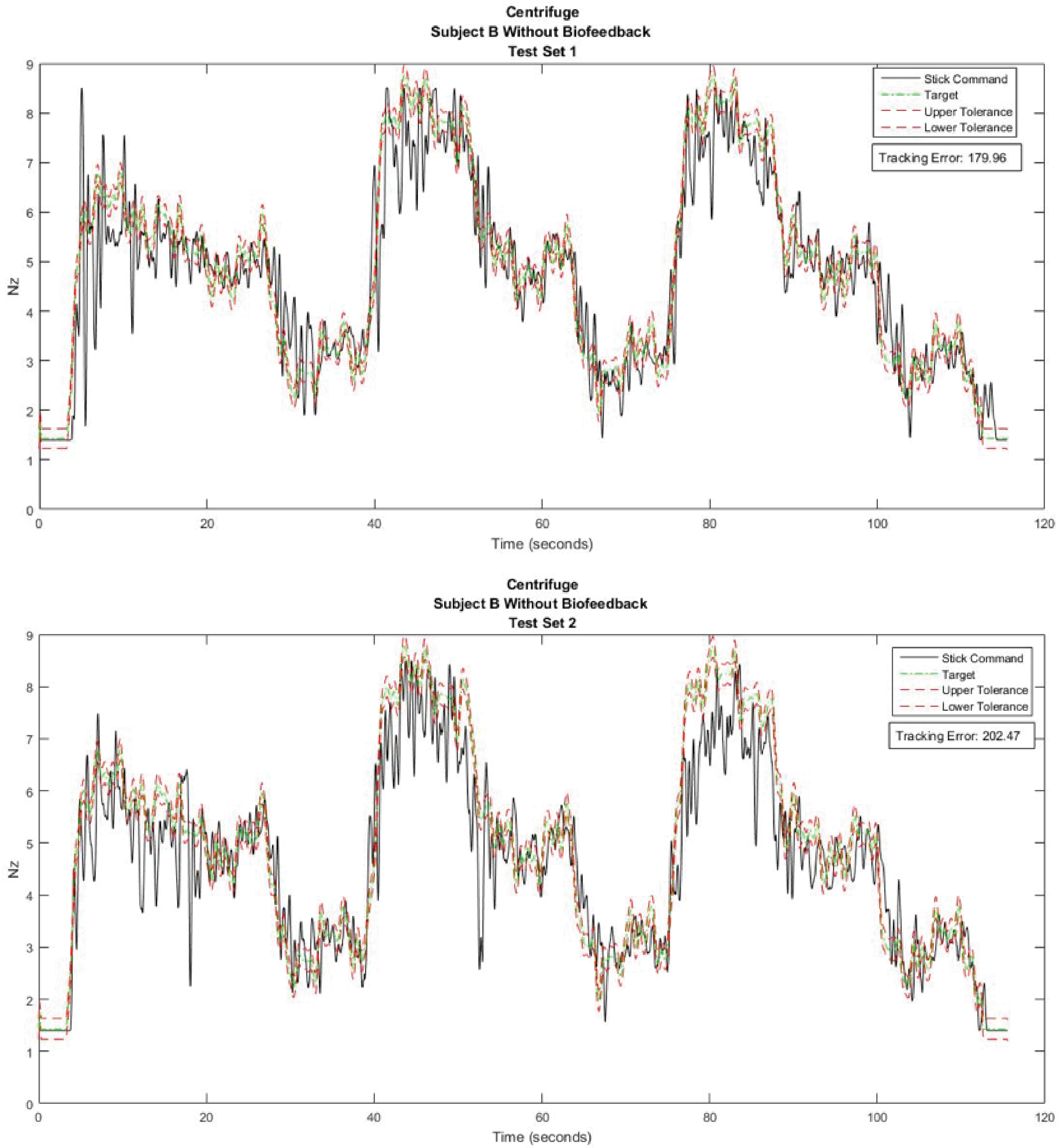
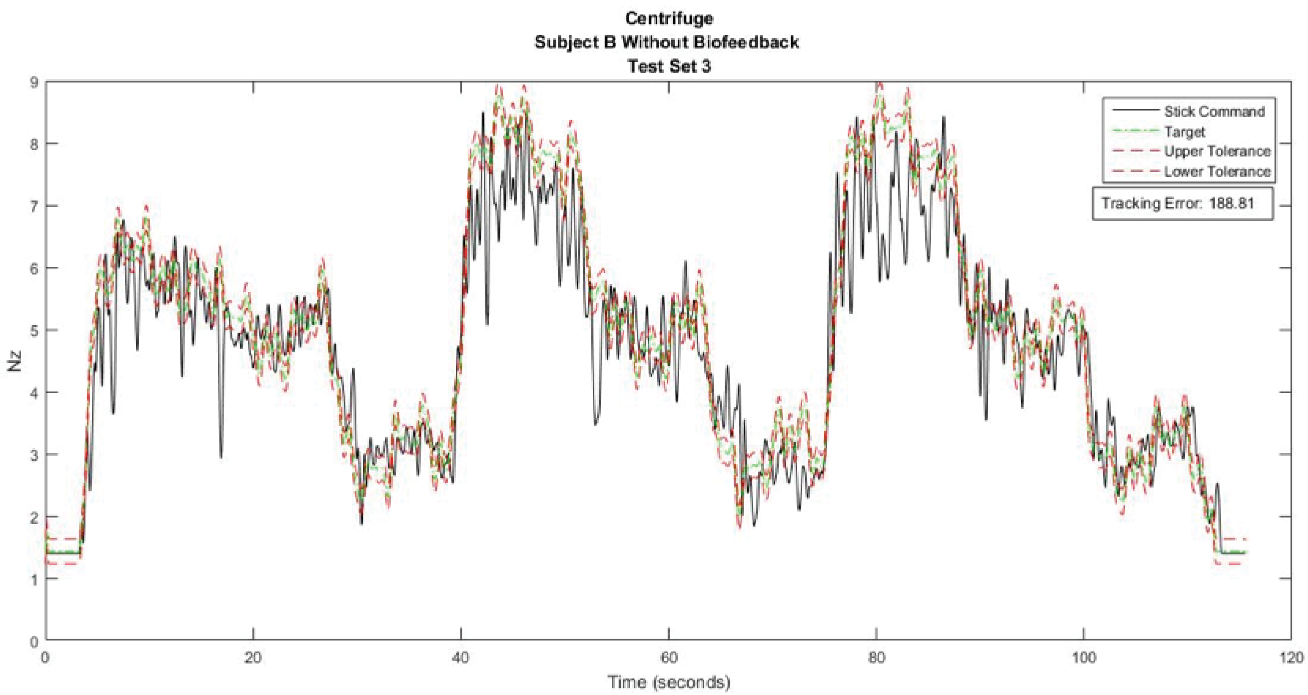


Figure 70: Subject B Phase 3 Without Biofeedback Test Sets 1-2



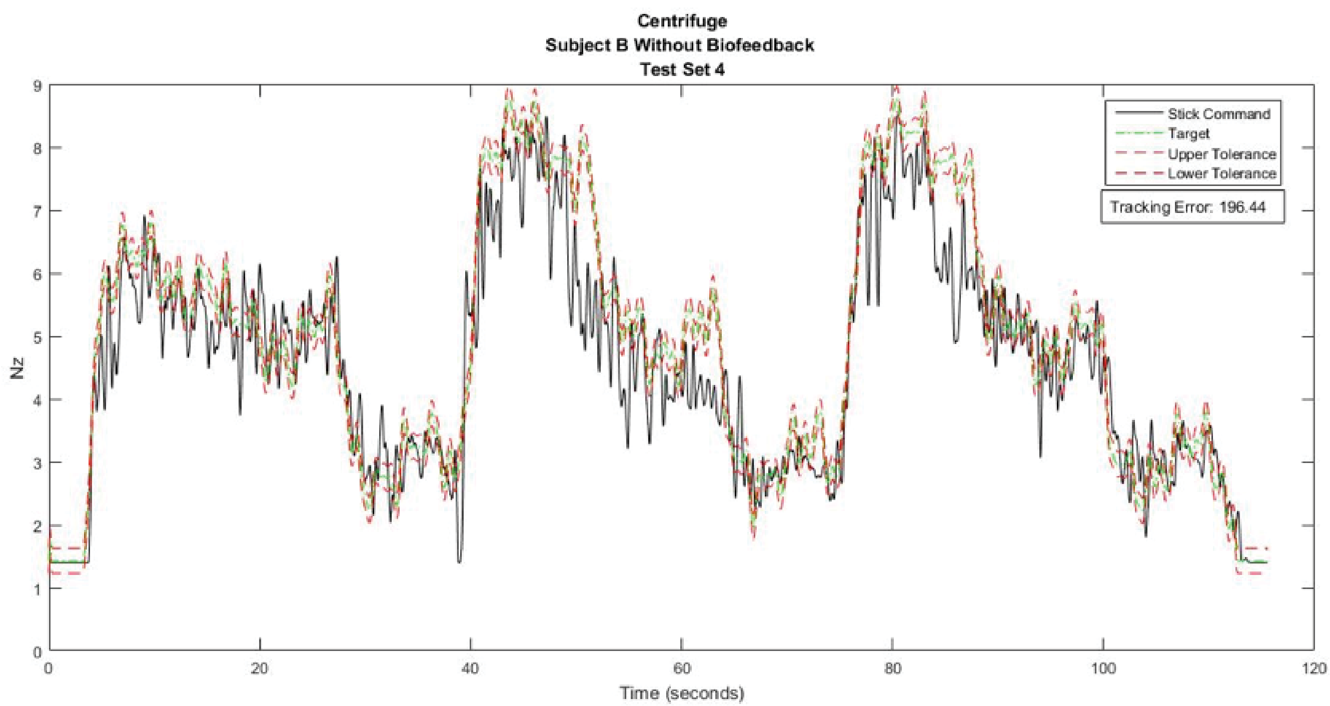


Figure 71: Subject B Phase 3 Without Biofeedback Test Sets 3-4

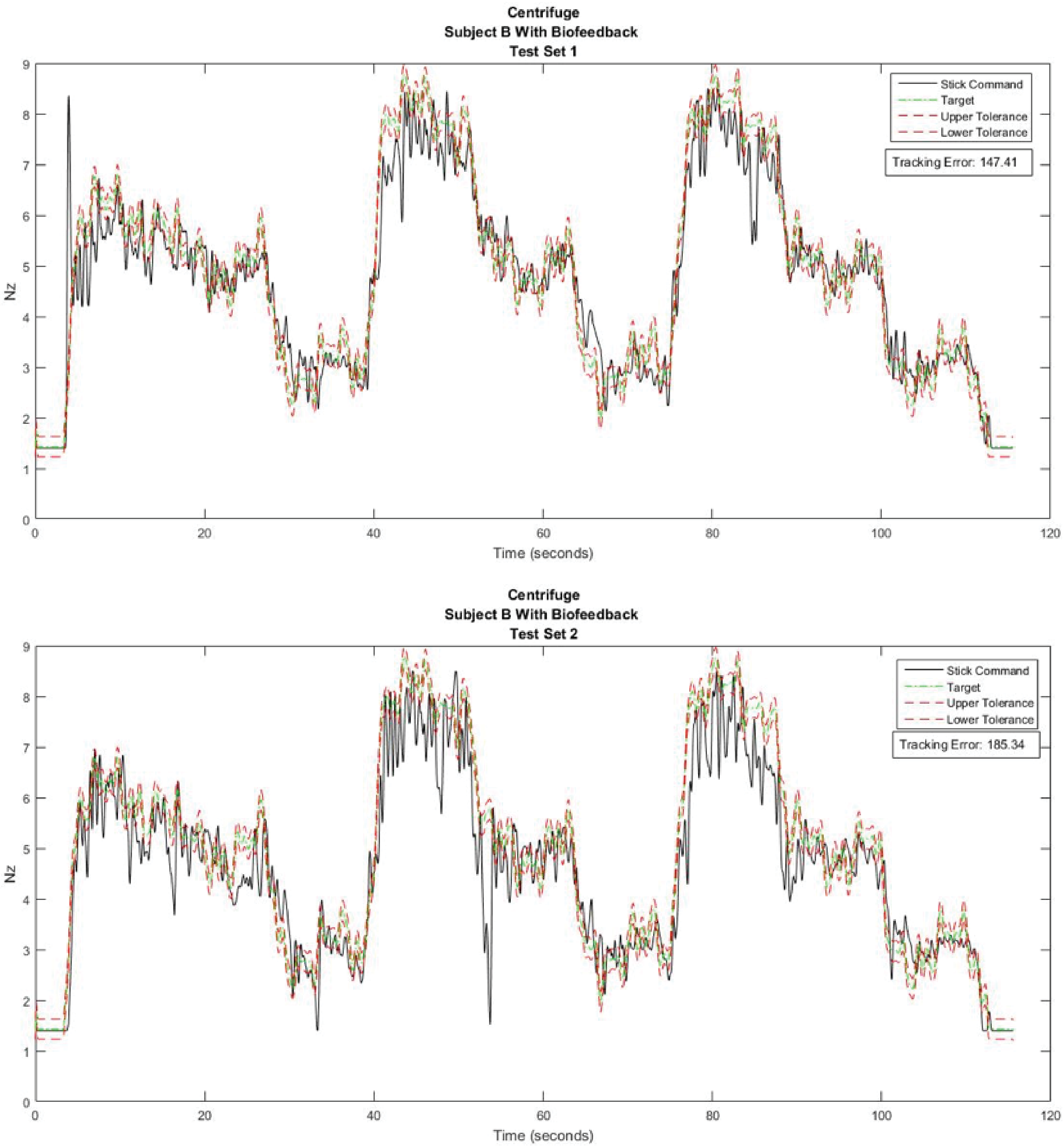
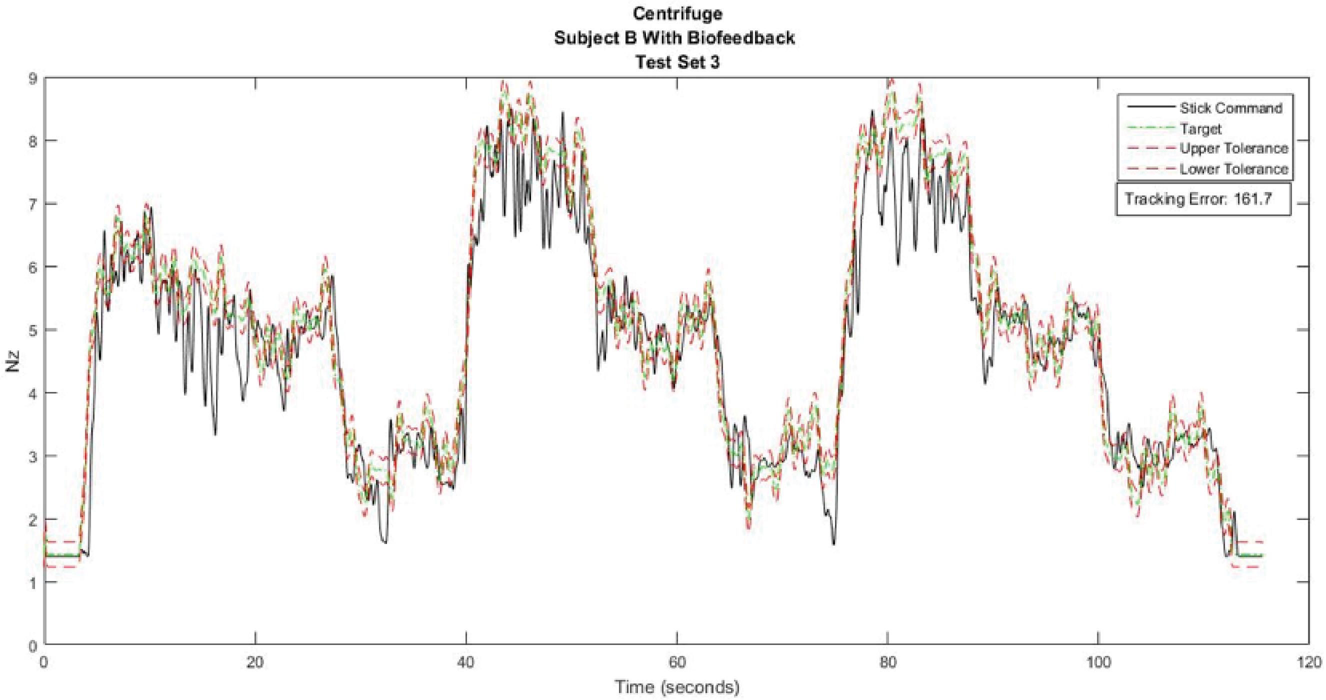


Figure 72: Subject B Phase 3 With Biofeedback Test Sets 1-2



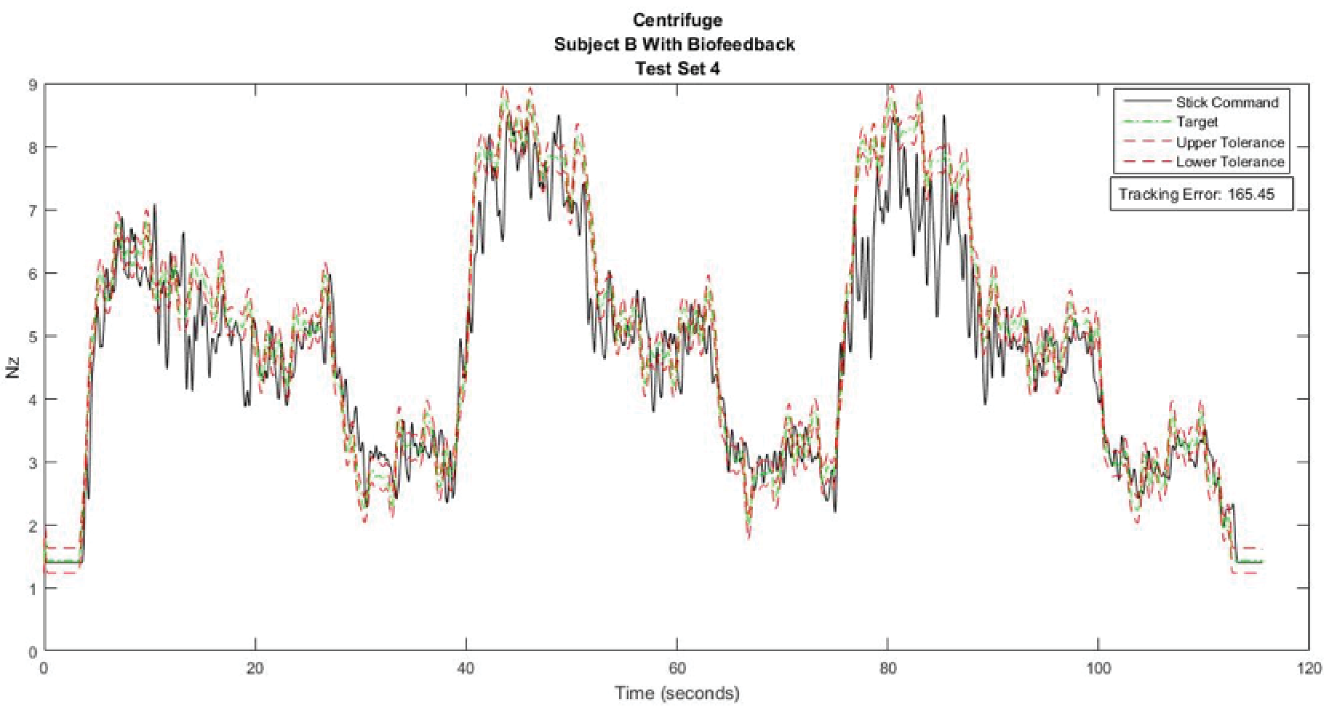


Figure 73: Subject B Phase 3 With Biofeedback Test Sets 3-4

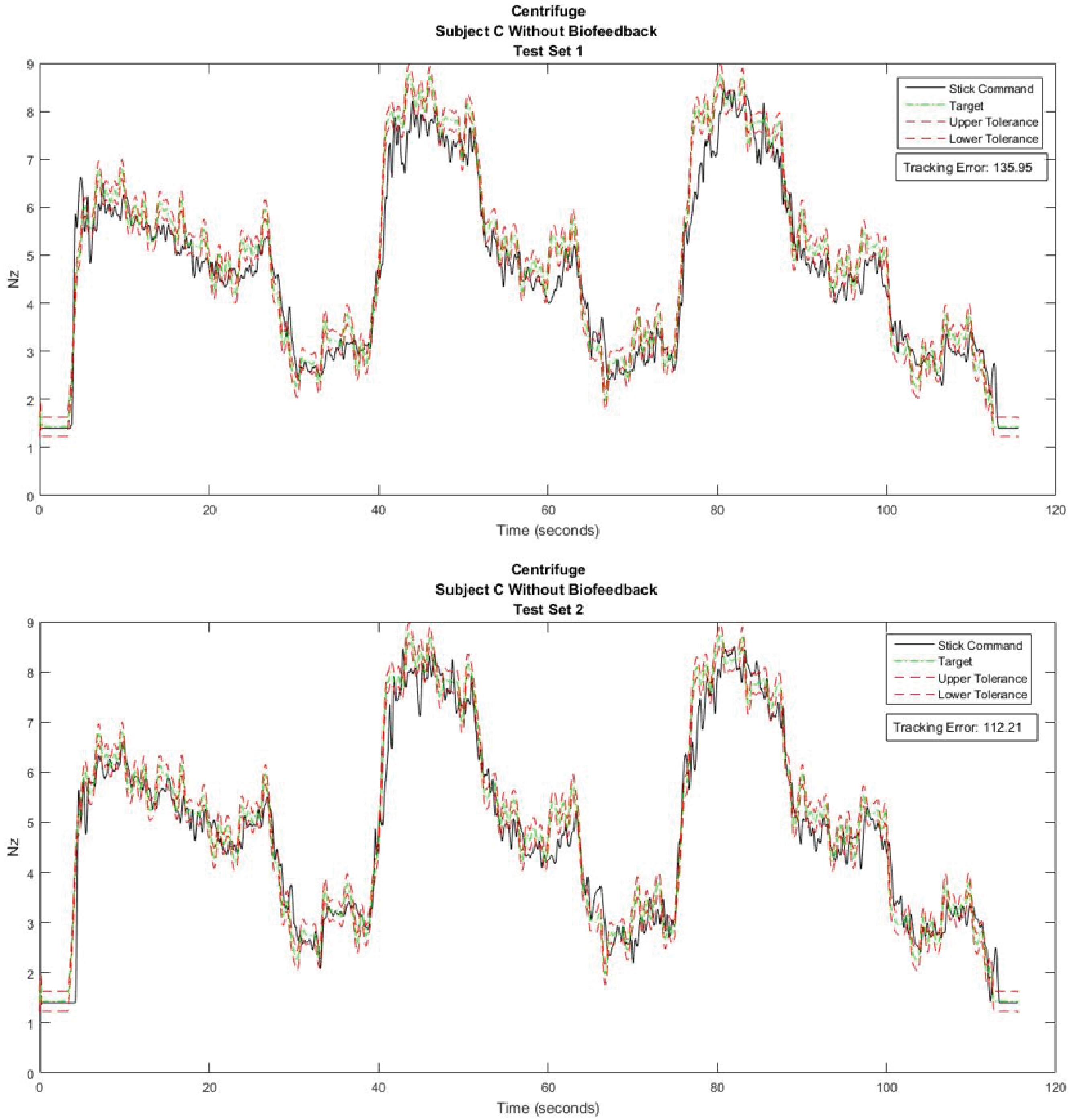


Figure 74: Subject C Phase 3 Without Biofeedback Test Sets 1-2

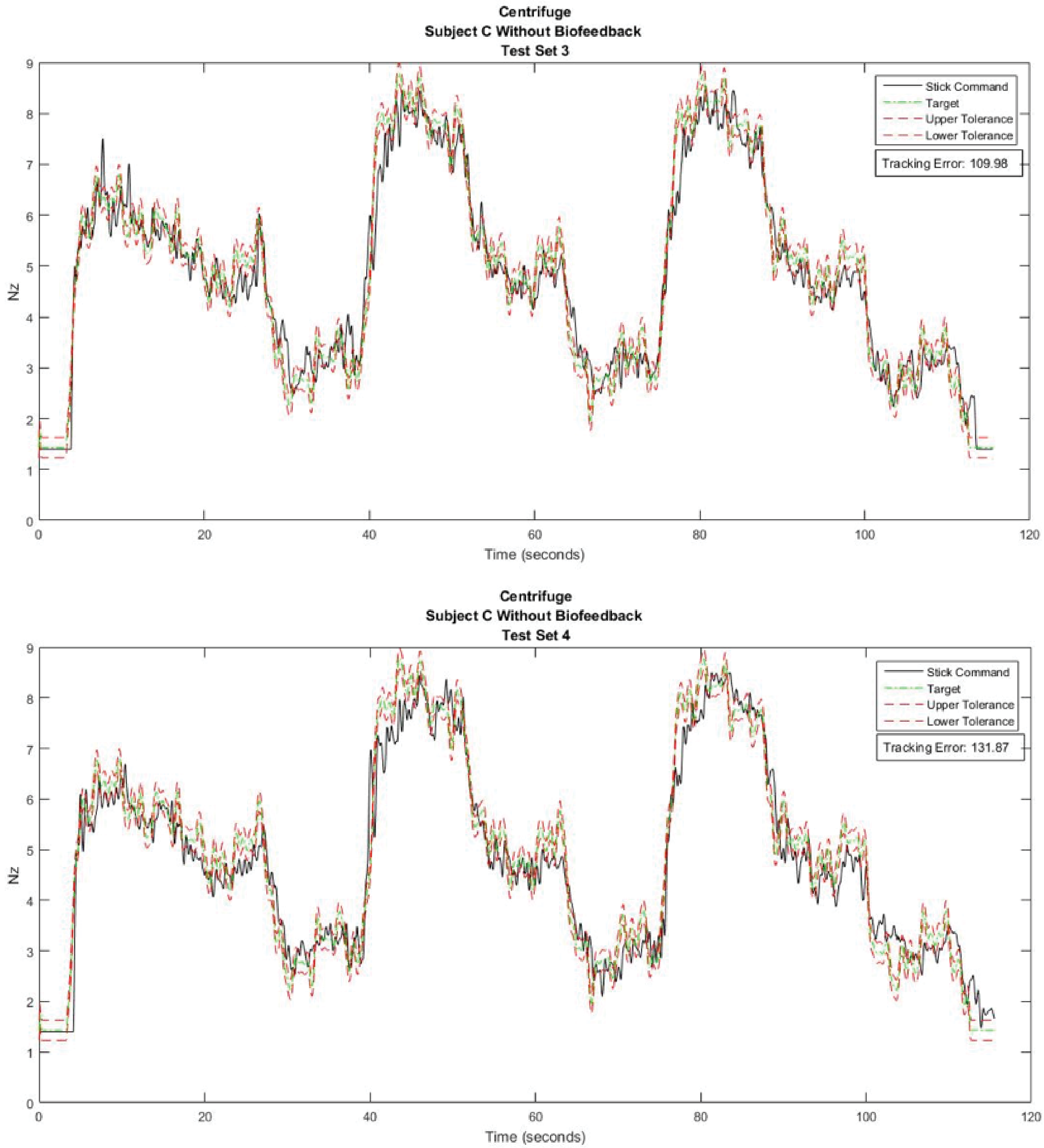


Figure 75: Subject C Phase 3 Without Biofeedback Test Sets 3-4

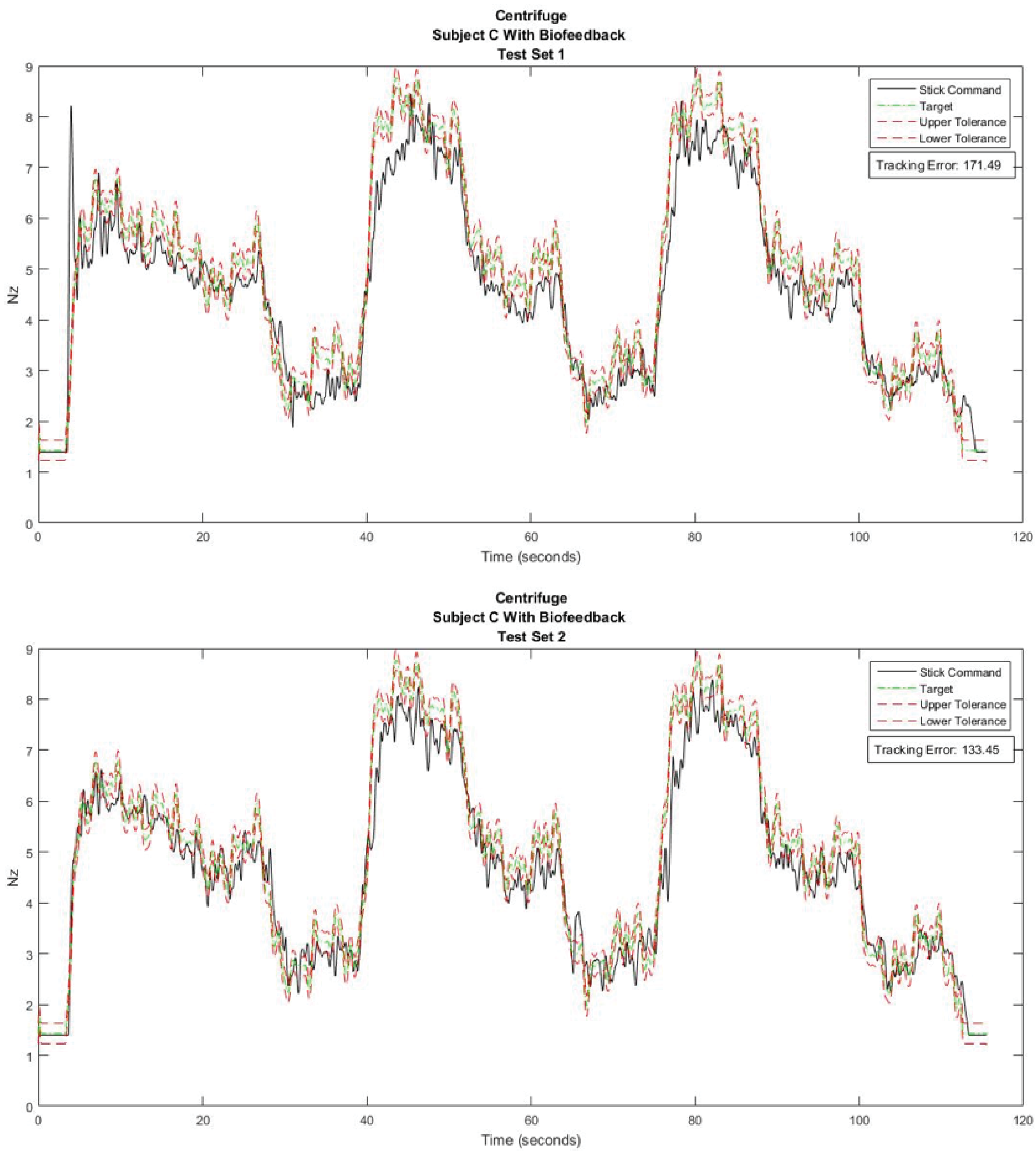
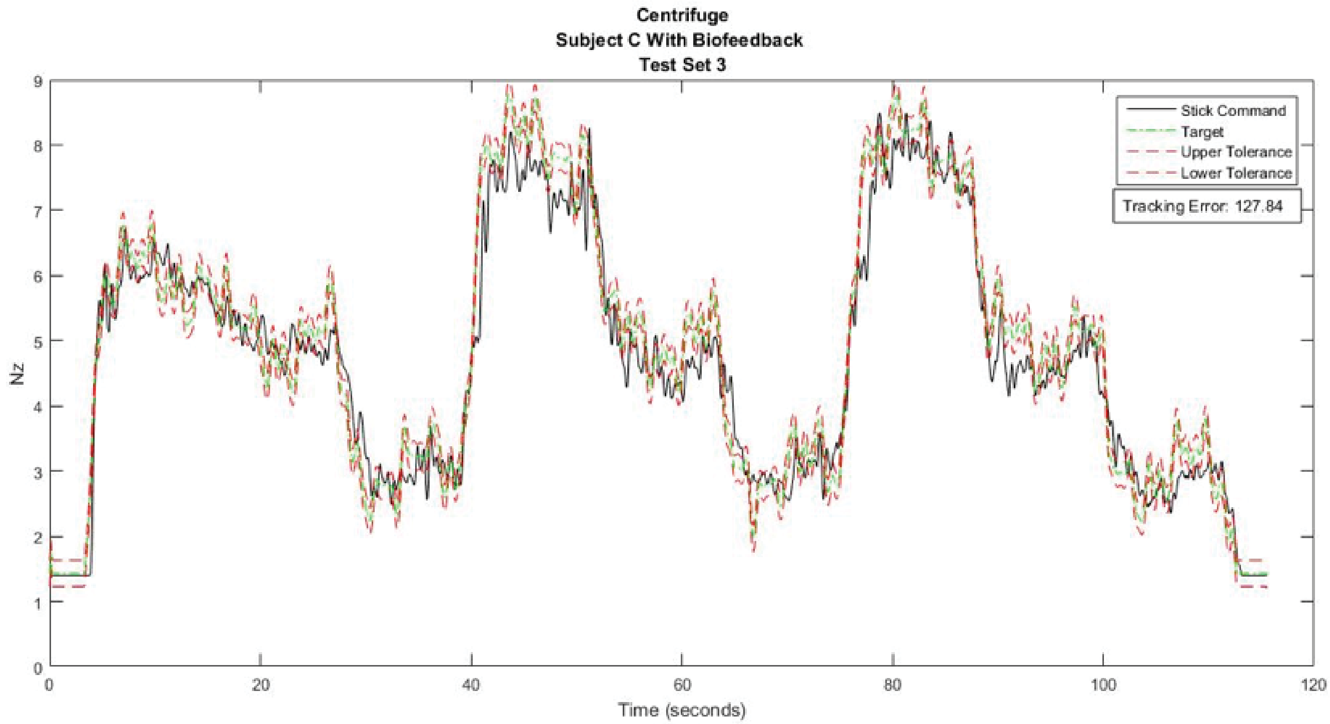


Figure 76: Subject C Phase 3 With Biofeedback Test Sets 1-2



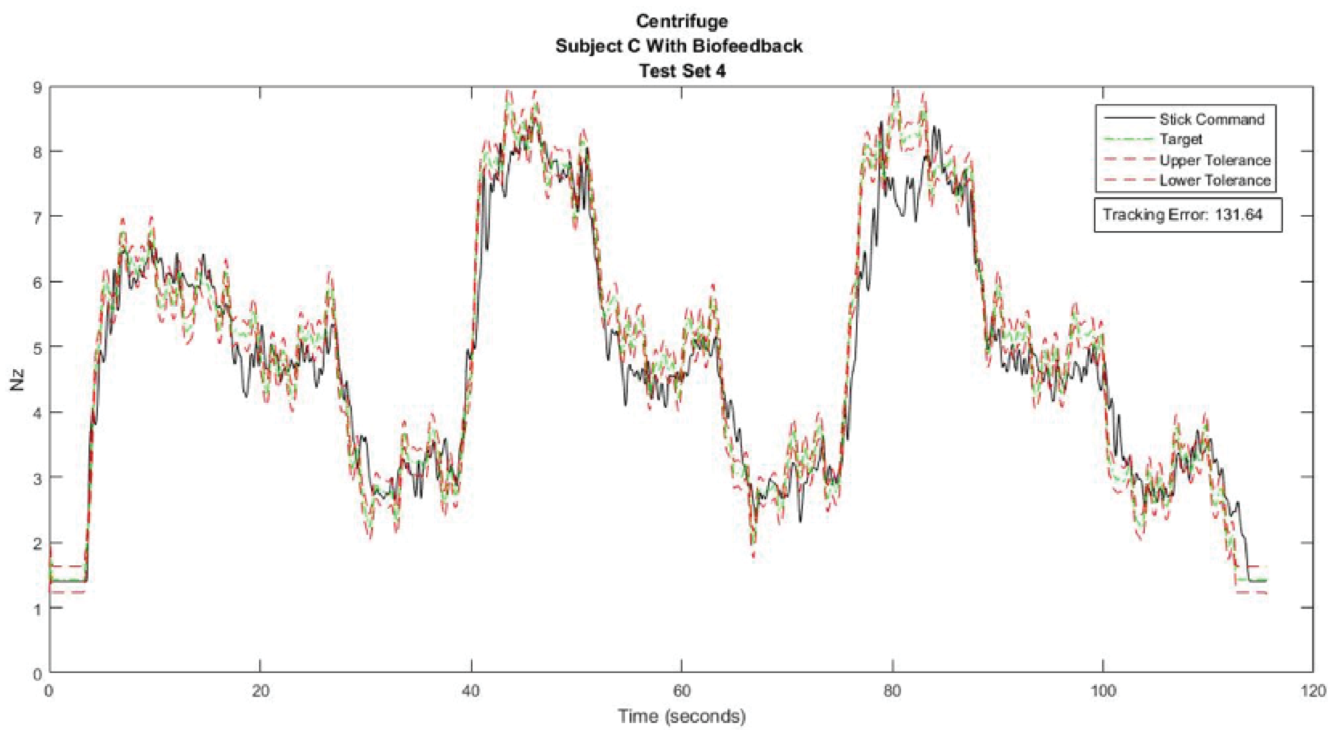


Figure 77: Subject C Phase 3 With Biofeedback Test Sets 3-4

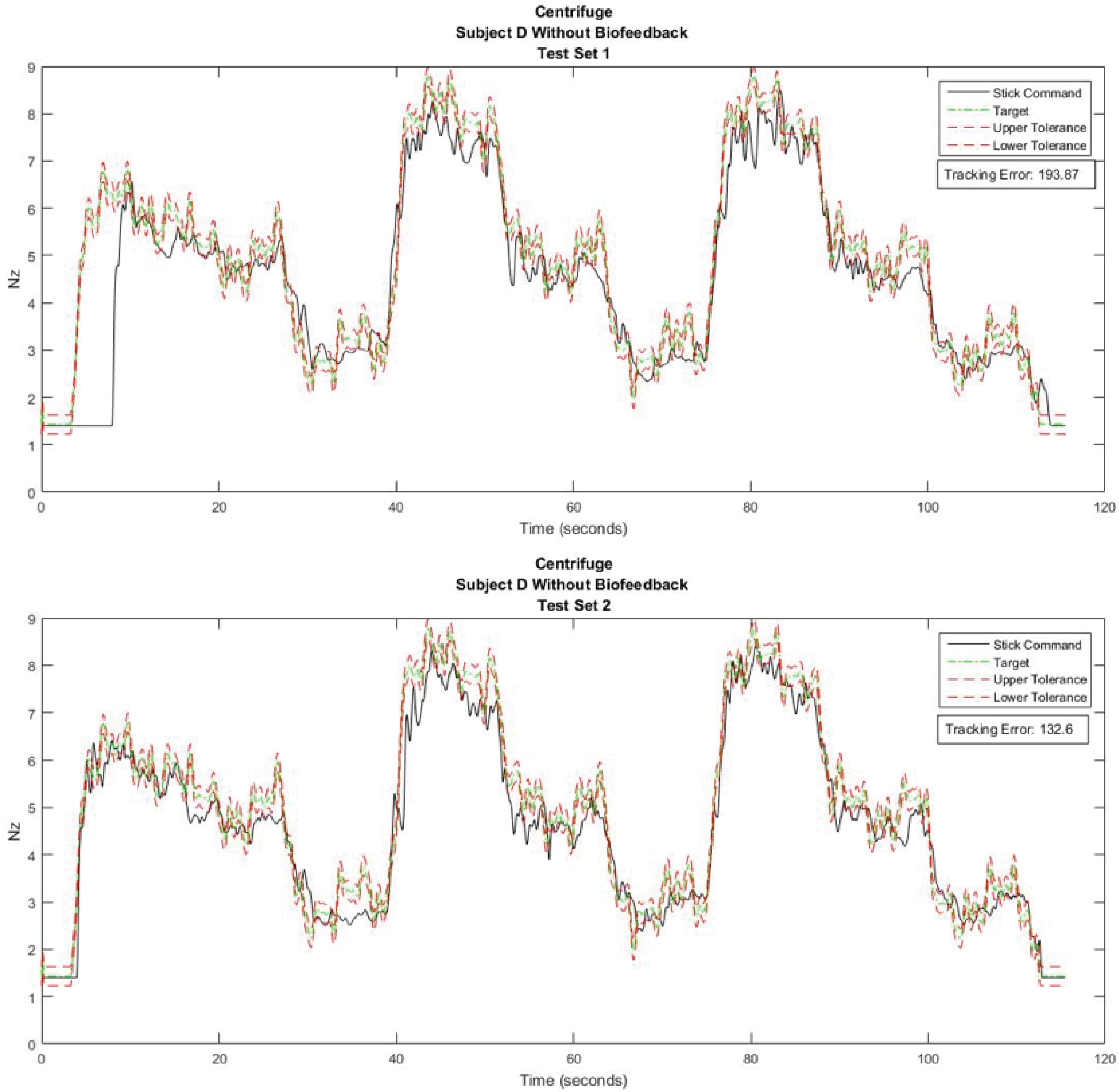
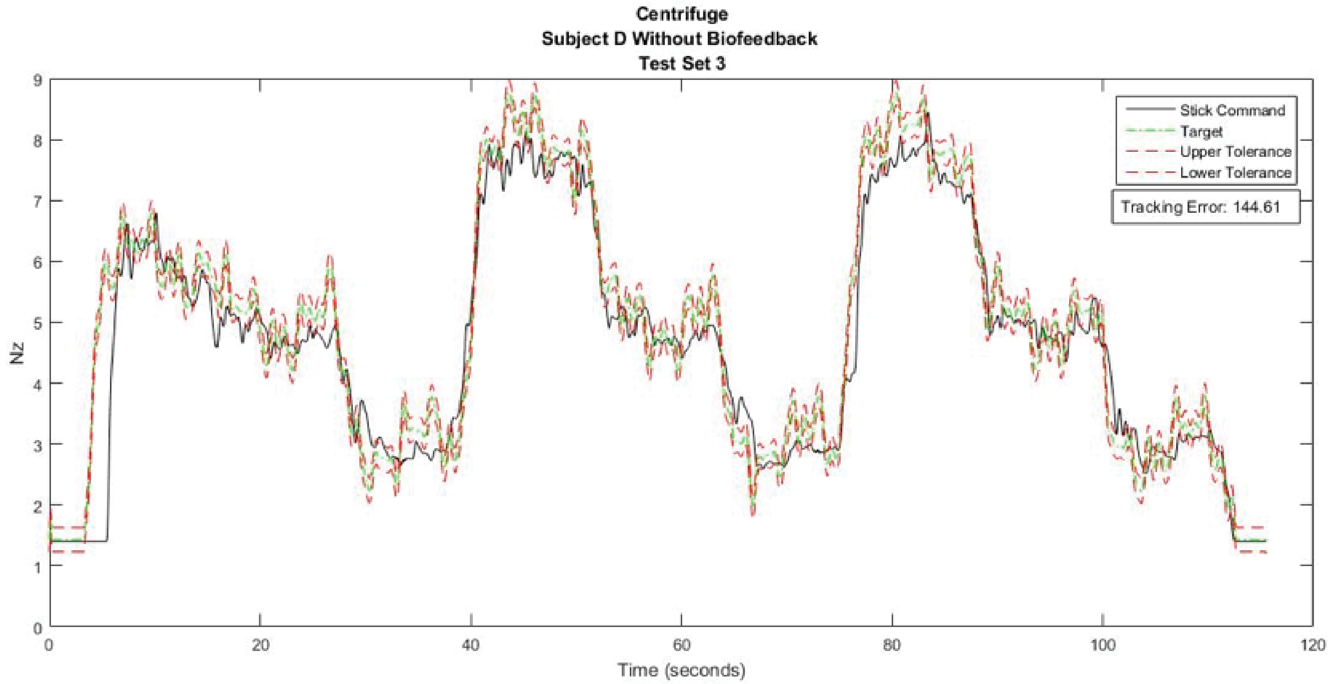


Figure 78: Subject D Phase 3 Without Biofeedback Test Sets 1-2



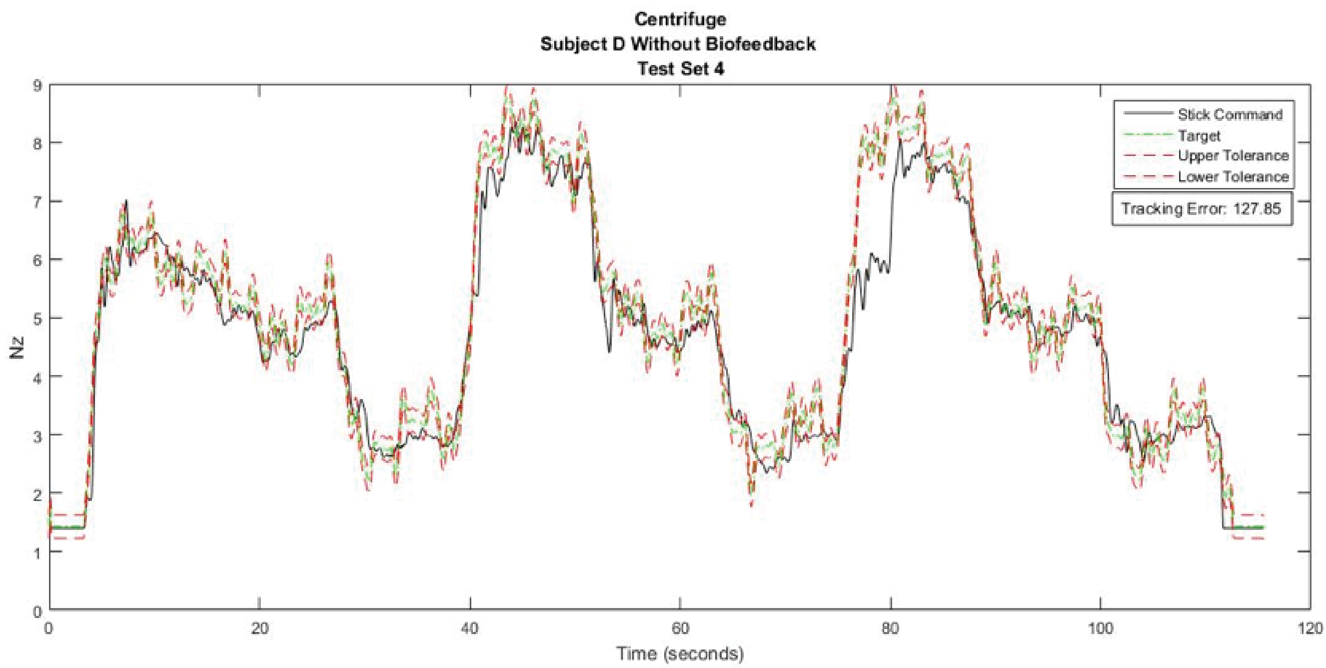


Figure 79: Subject D Phase 3 Without Biofeedback Test Sets 3-4

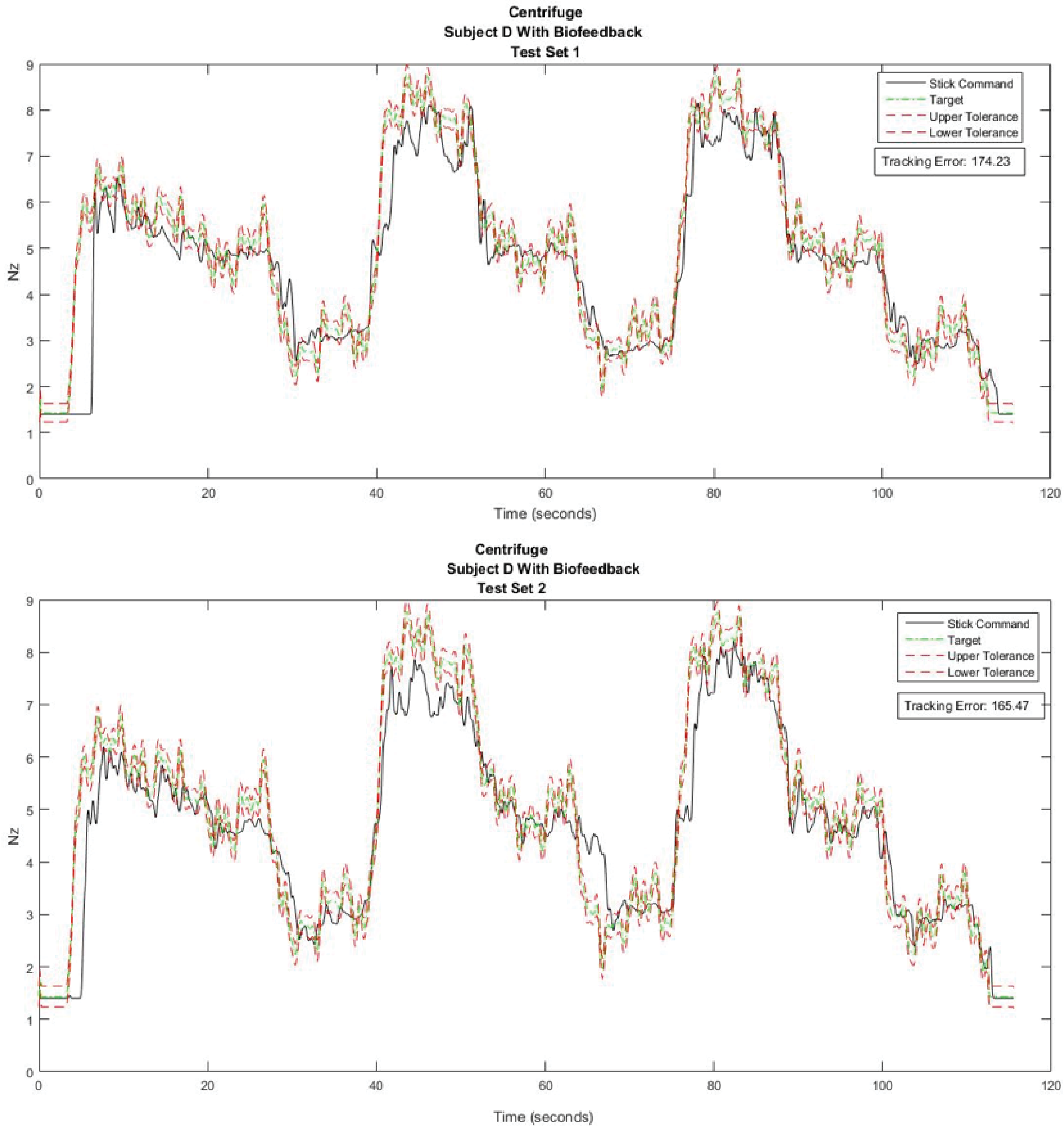


Figure 80: Subject D Phase 3 With Biofeedback Test Sets 1-2

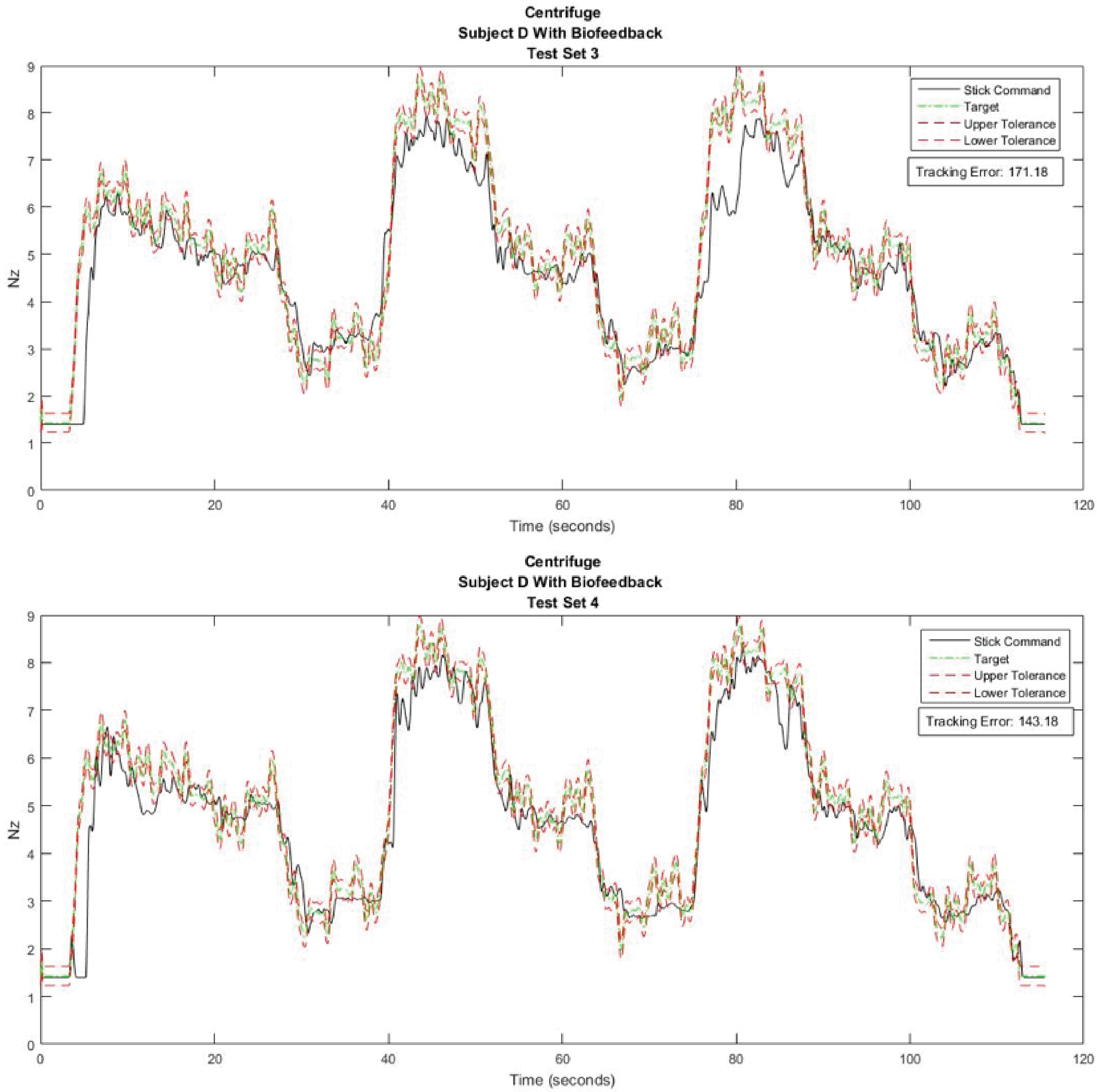
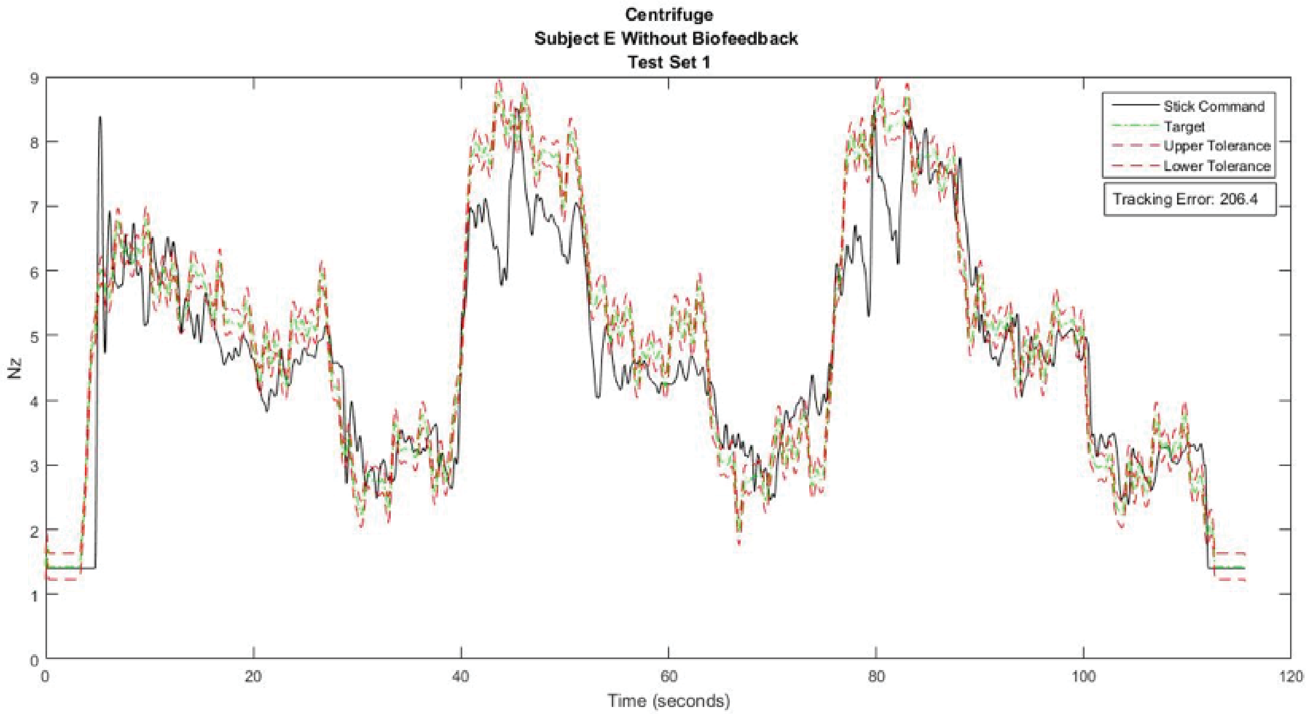


Figure 81: Subject D Phase 3 With Biofeedback Test Sets 3-4



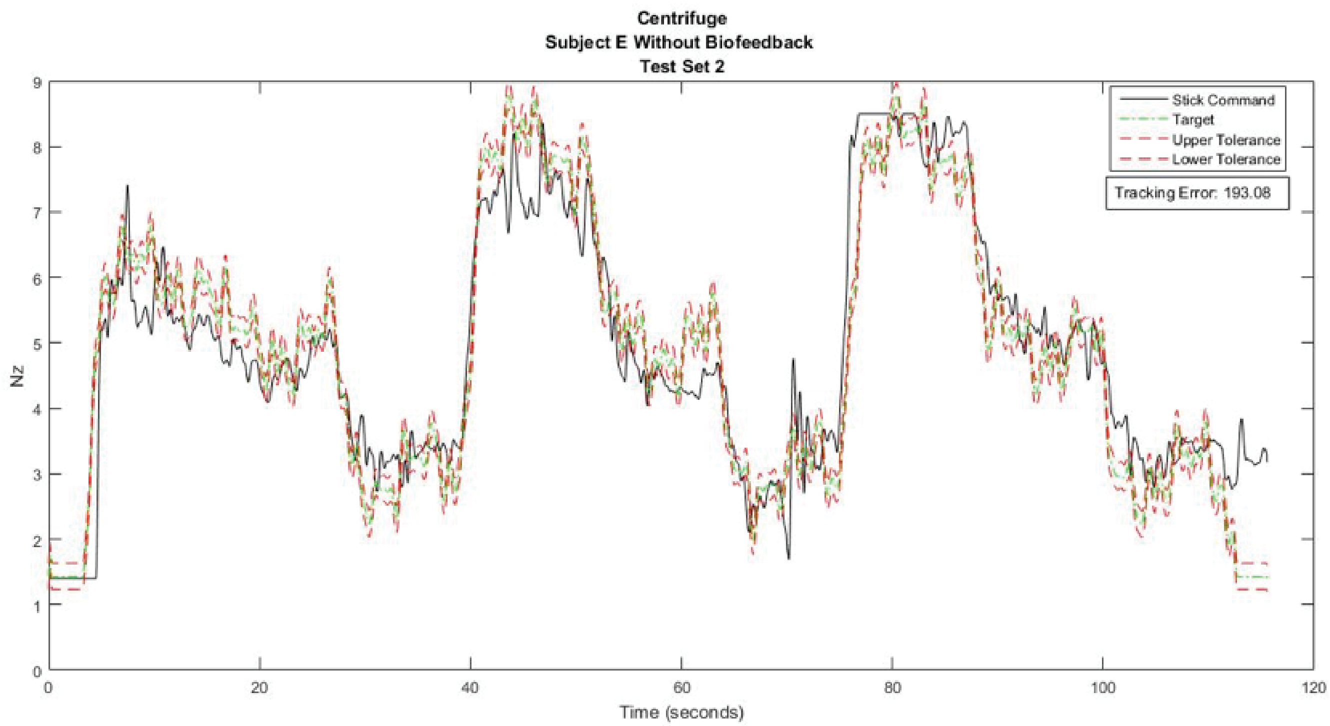
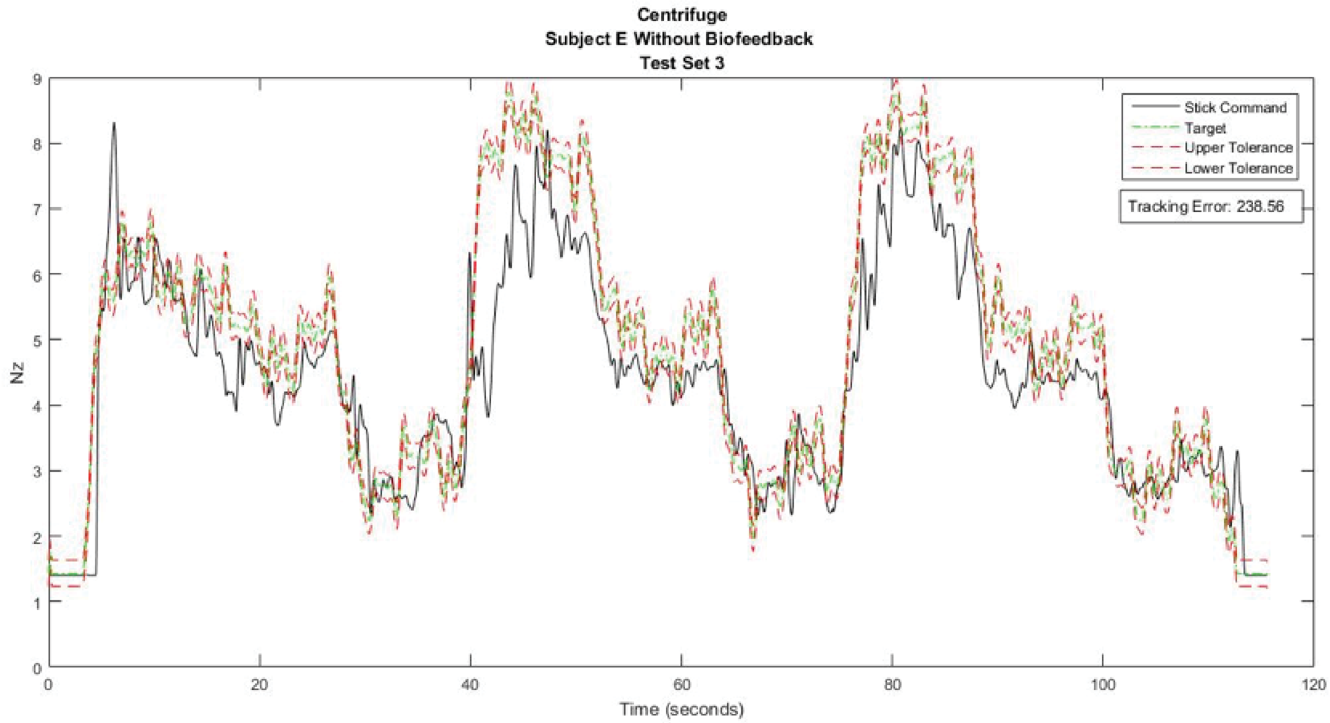


Figure 82: Subject E Phase 3 Without Biofeedback Test Sets 1-2



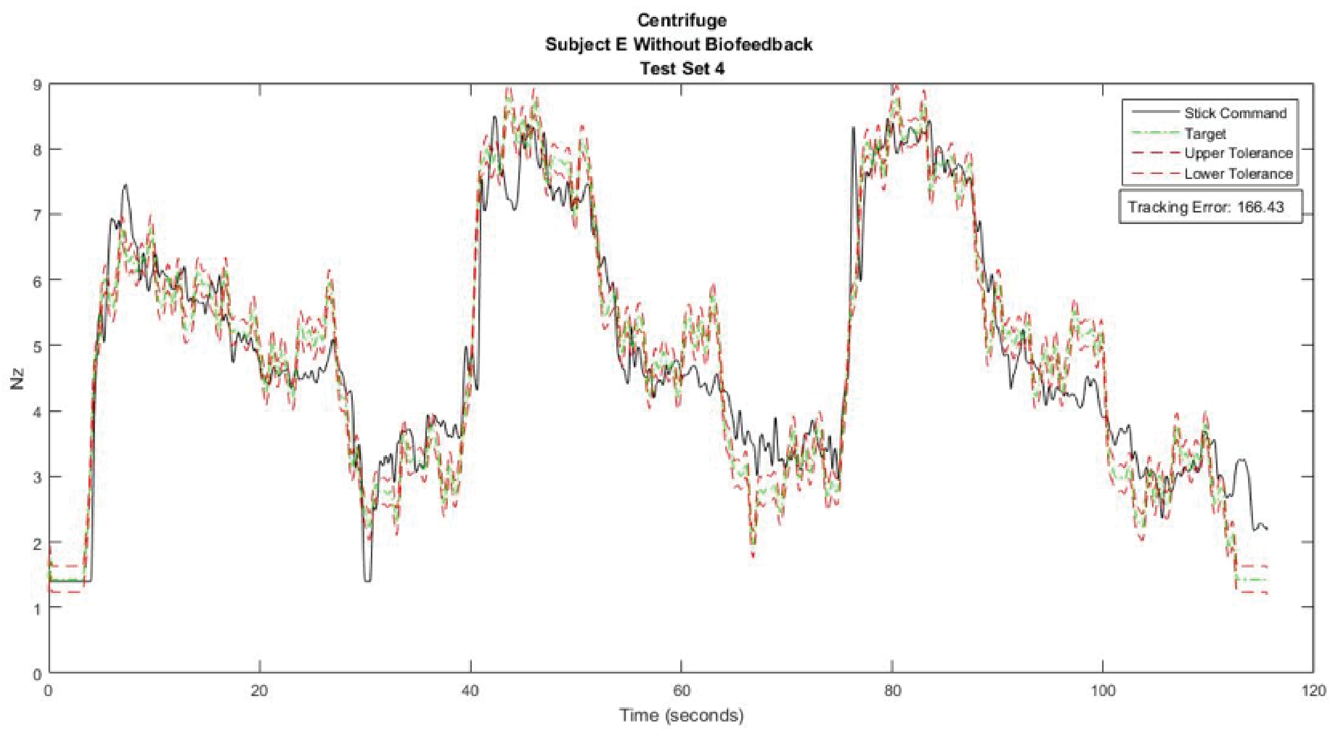


Figure 83: Subject E Phase 3 Without Biofeedback Test Sets 3-4

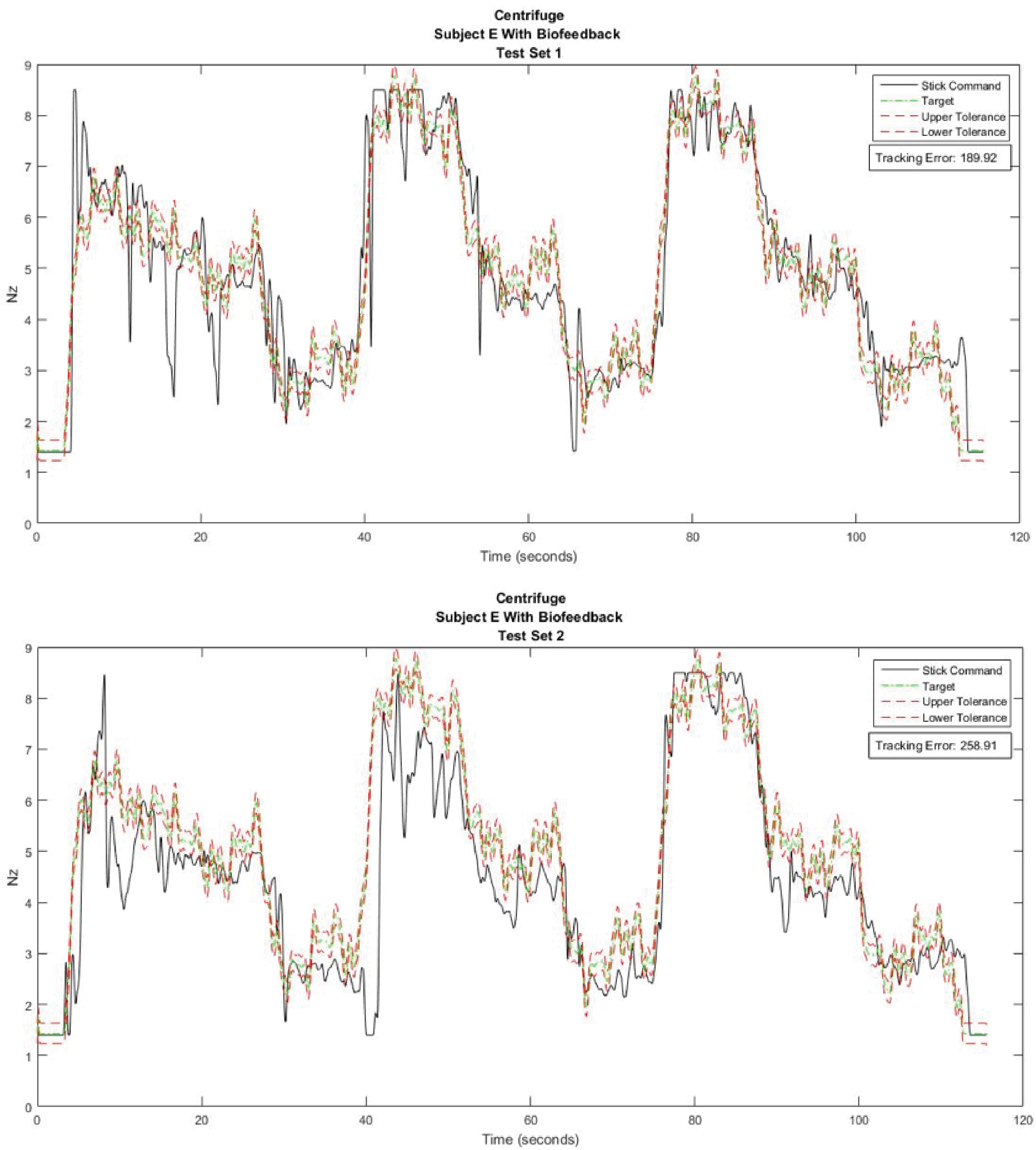


Figure 84: Subject E Phase 3 With Biofeedback Test Sets 1-2

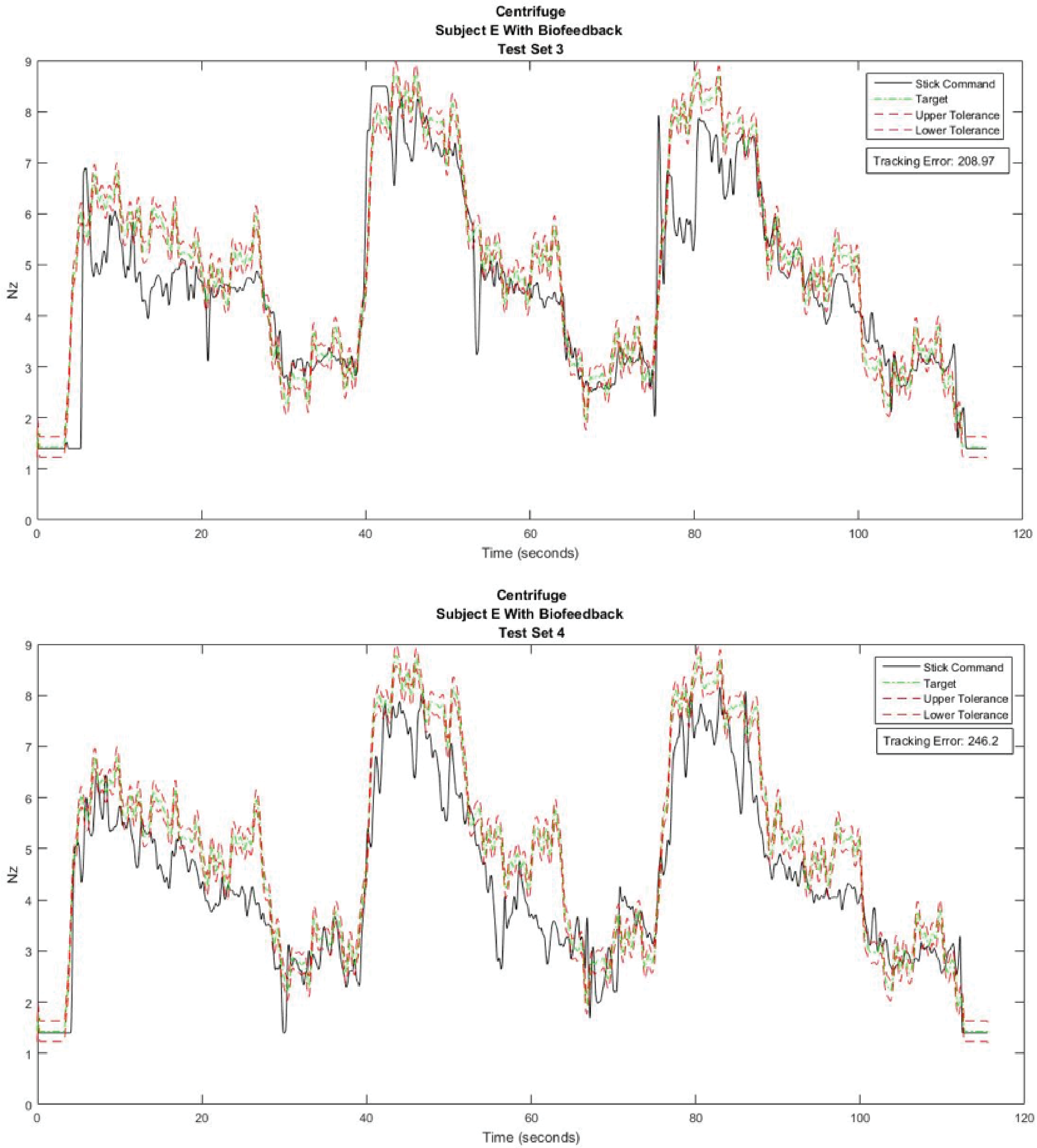


Figure 85: Subject E Phase 3 With Biofeedback Test Sets 3-4

Appendix G – Subject B and C Phase 4 %HRR vs. G

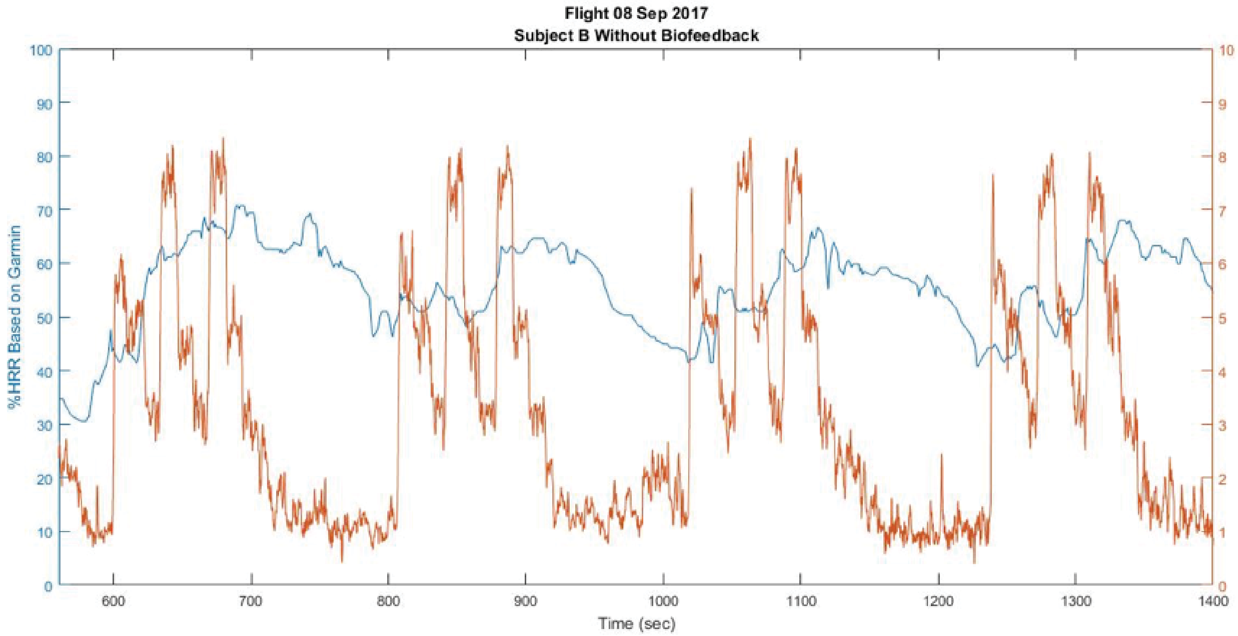


Figure 86: Subject B Phase 4 %HRR vs. G Without Biofeedback

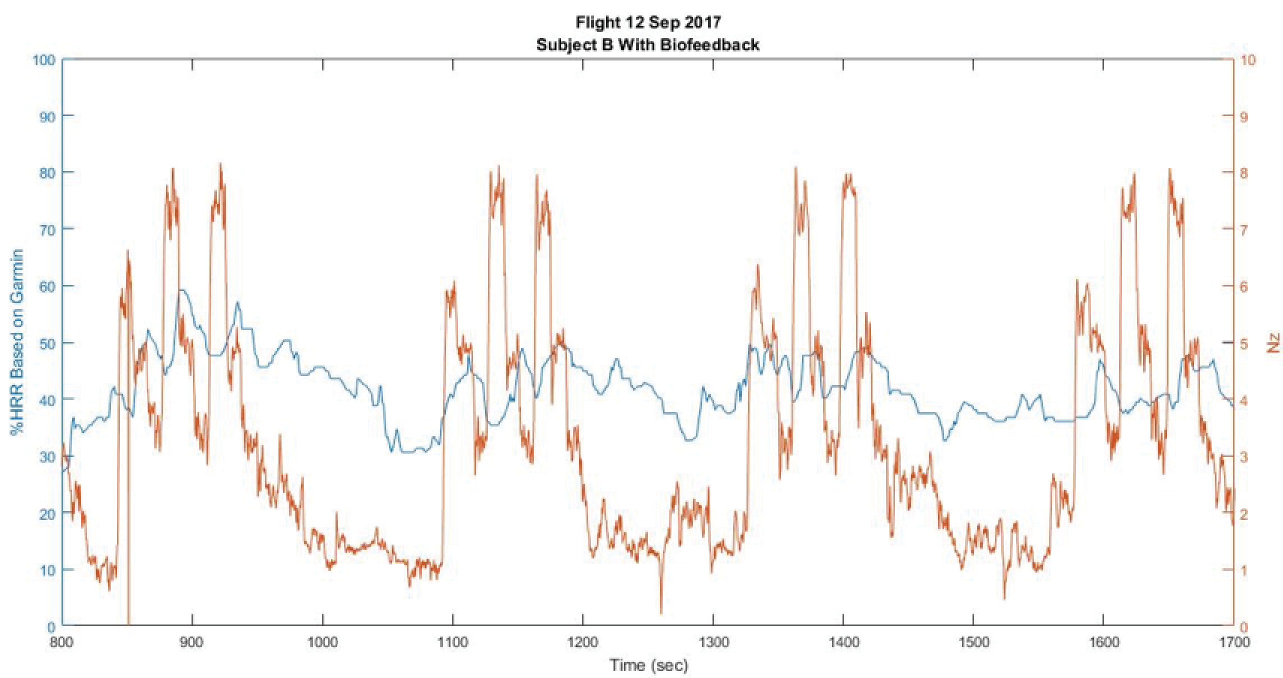


Figure 87: Subject B Phase 4 %HRR vs. G With Biofeedback

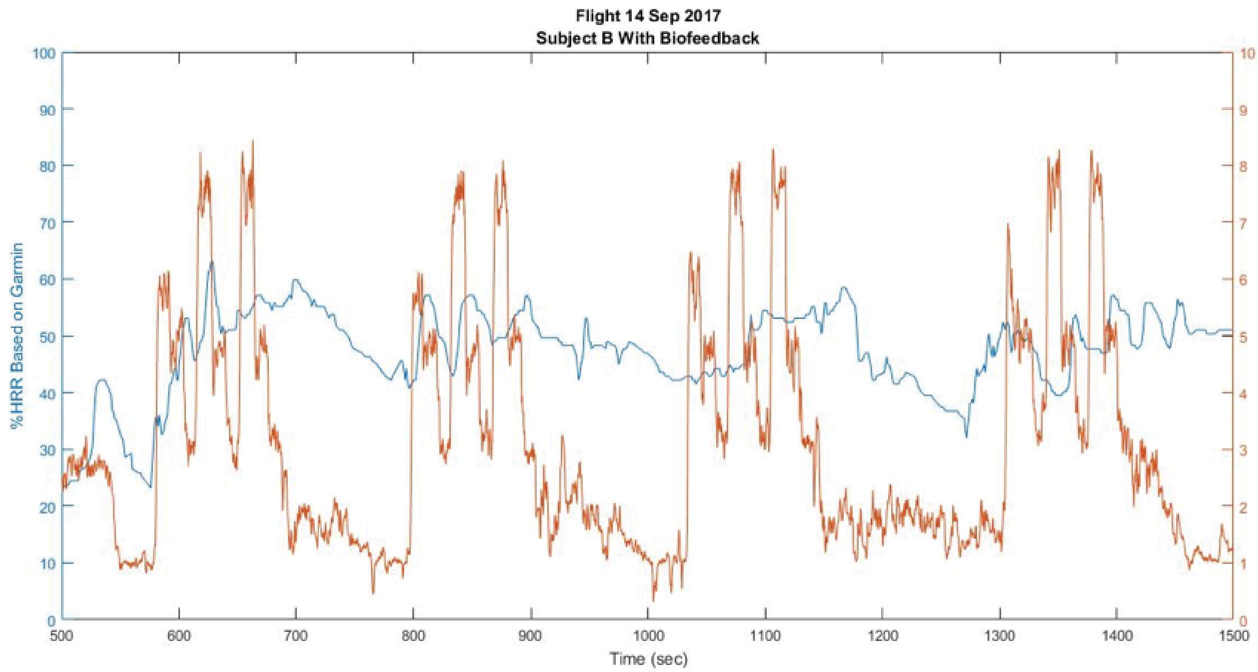


Figure 88: Subject B Phase 4 %HRR vs. G With Biofeedback

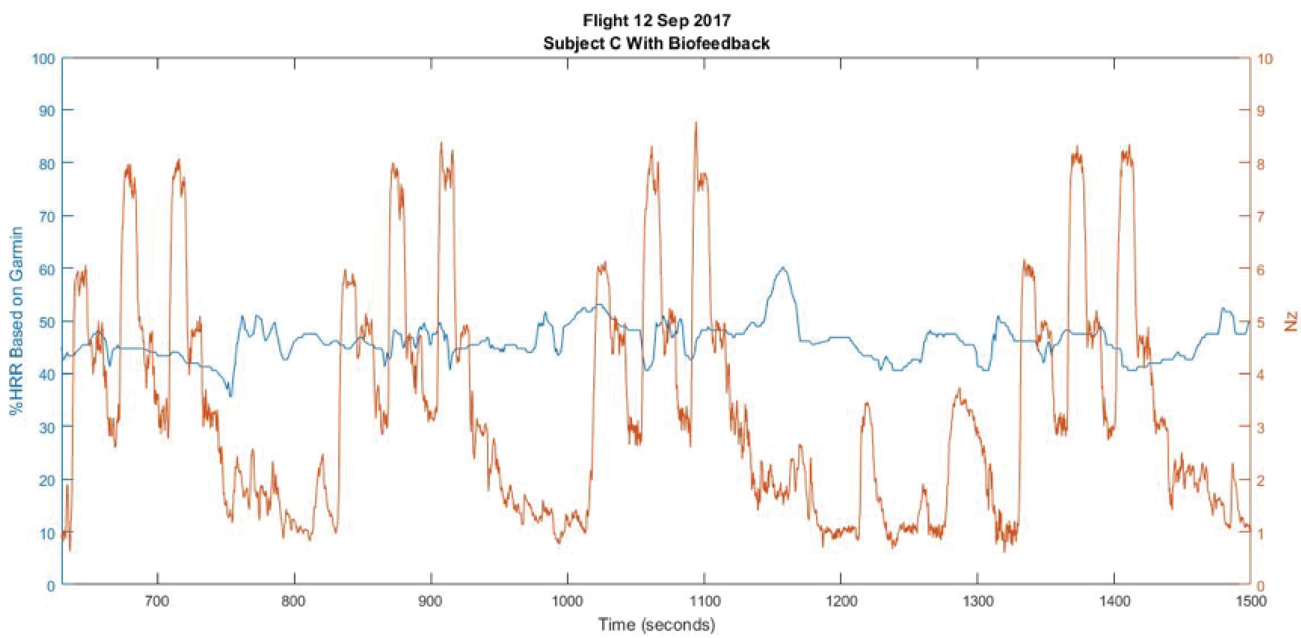


Figure 89: Subject C Phase 4 %HRR vs. G With Biofeedback

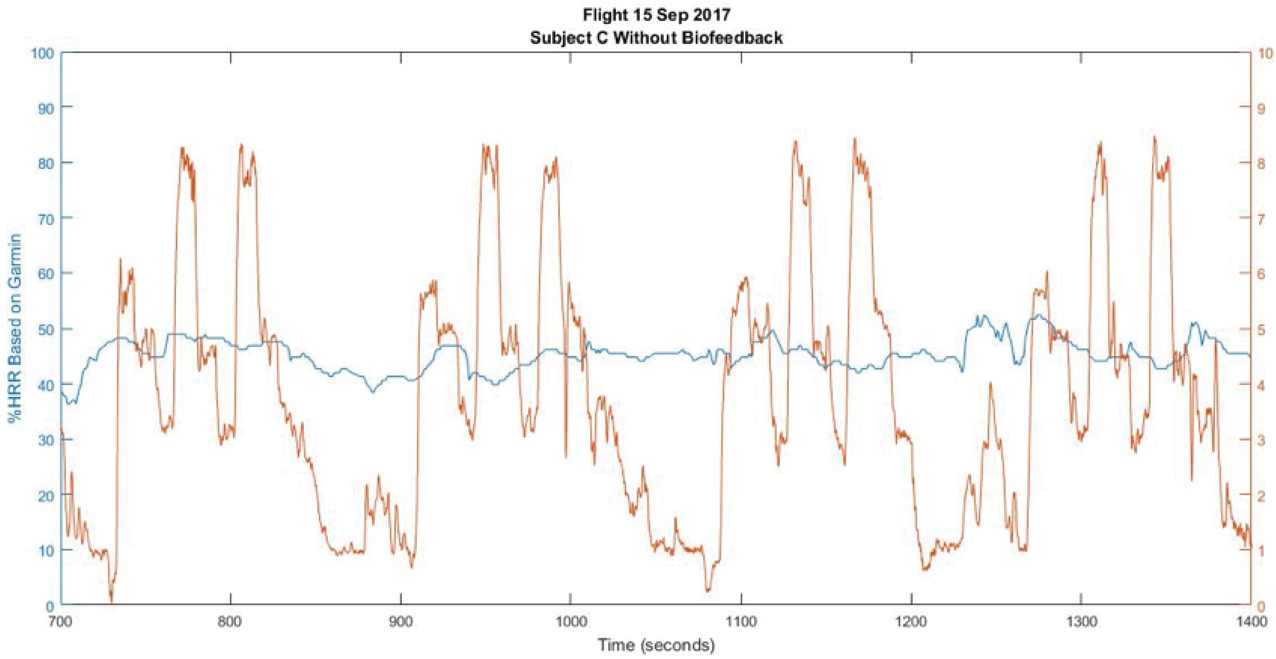


Figure 90: Subject C Phase 4 %HRR vs. G Without Biofeedback

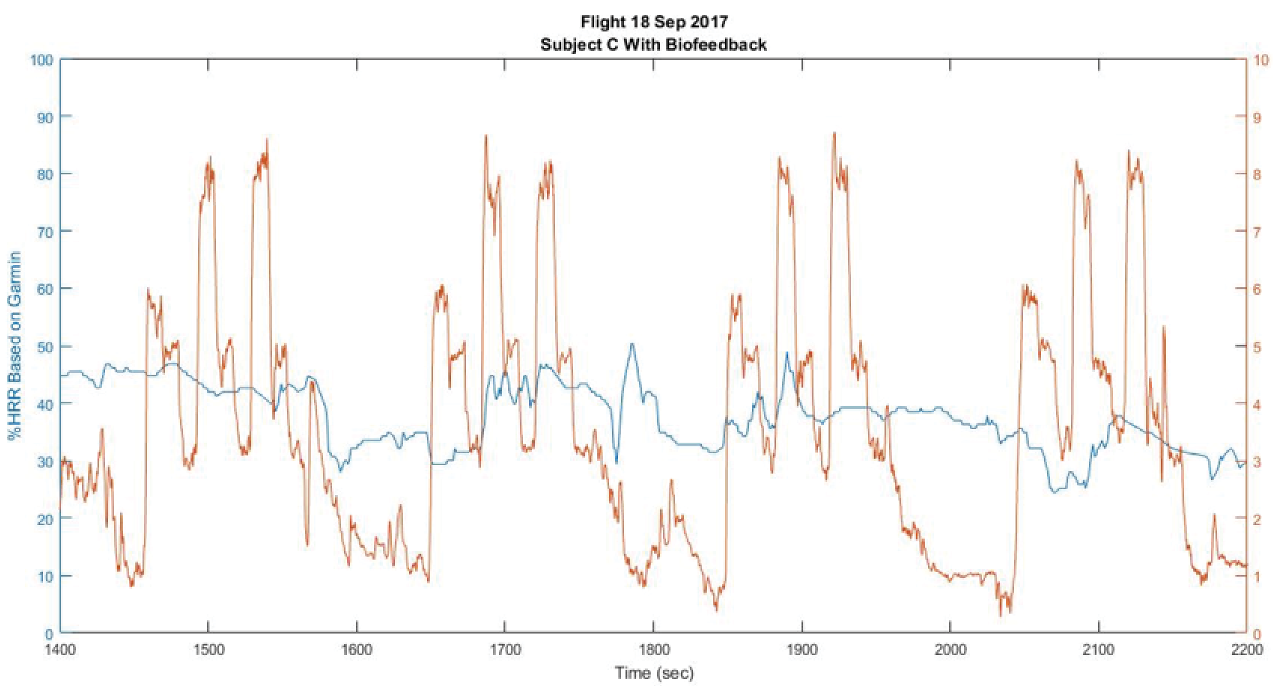
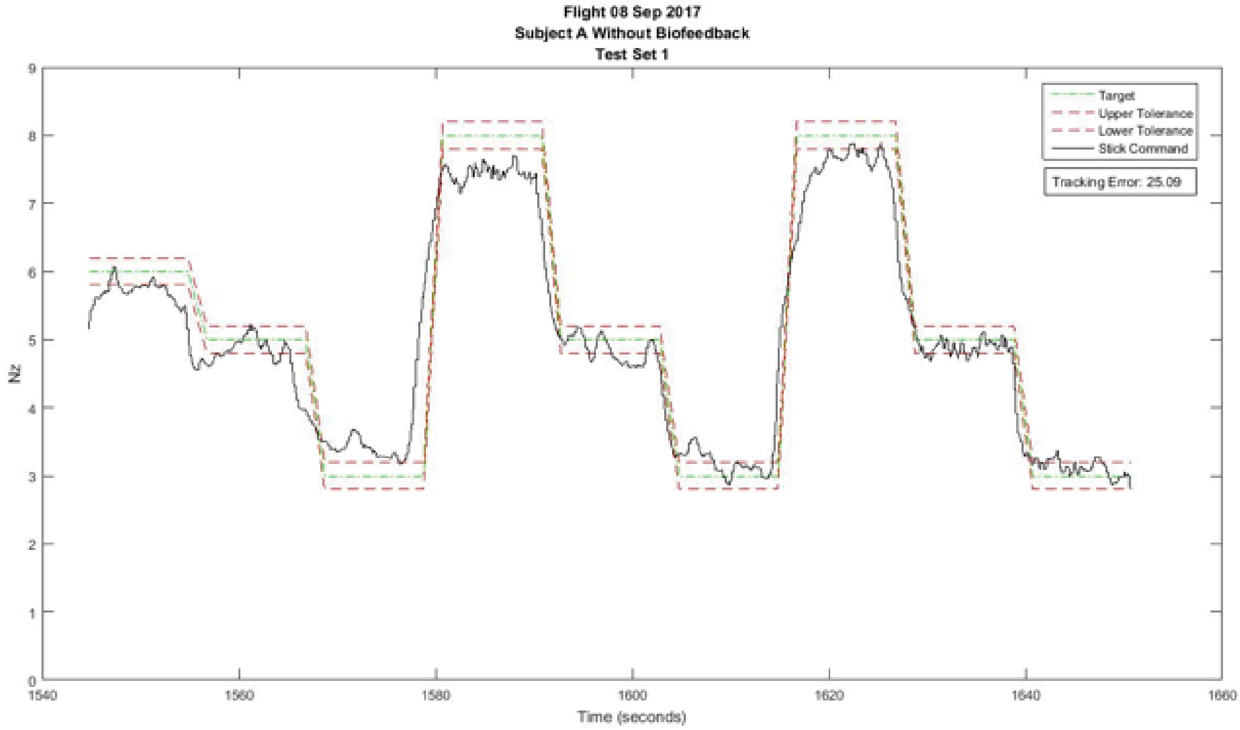


Figure 91: Subject C Phase 4 %HRR vs. G With Biofeedback

Appendix H – Subjects A-C Phase 4 G-Tracking Scores



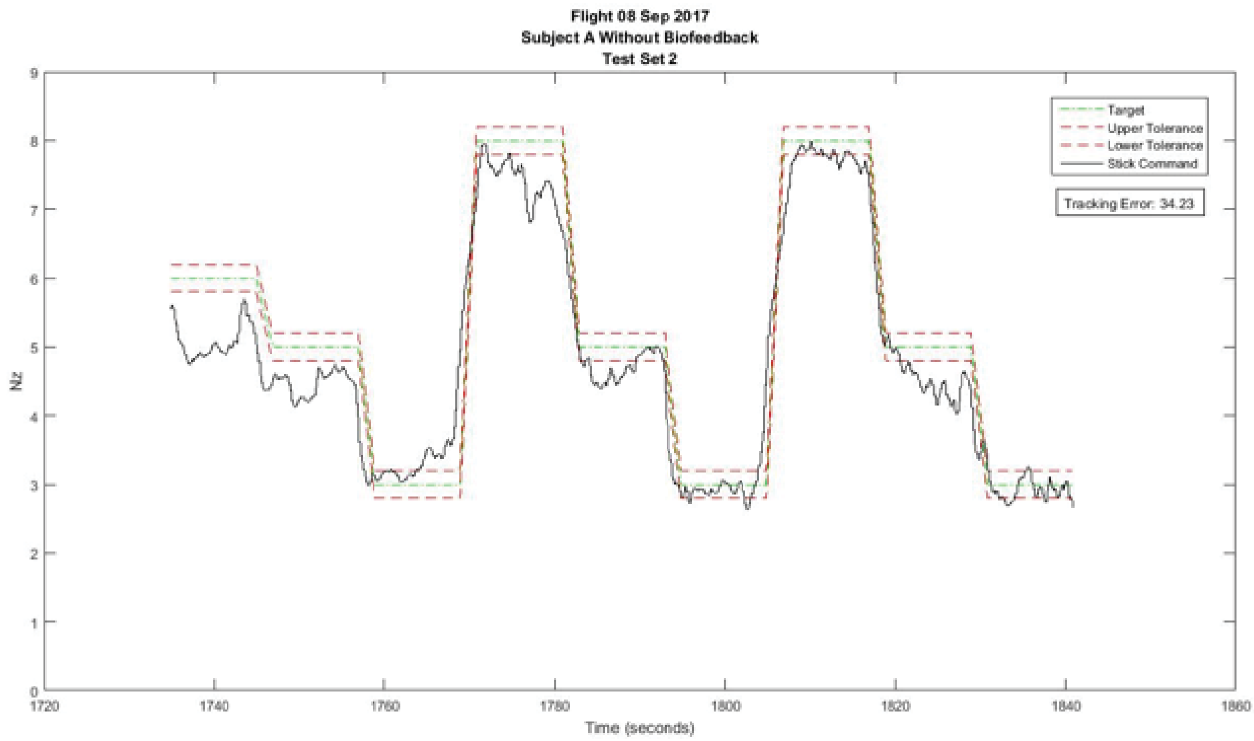
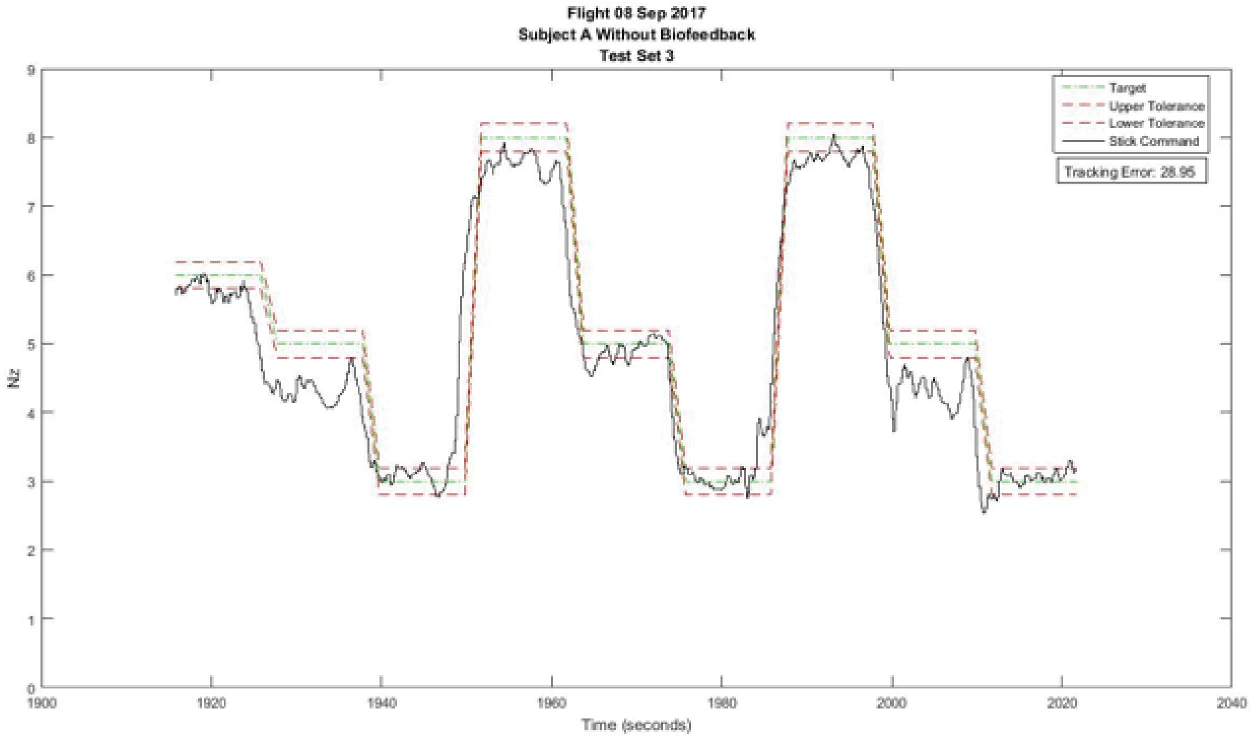


Figure 92: Subject A Phase 4 Without Biofeedback Test Sets 1-2



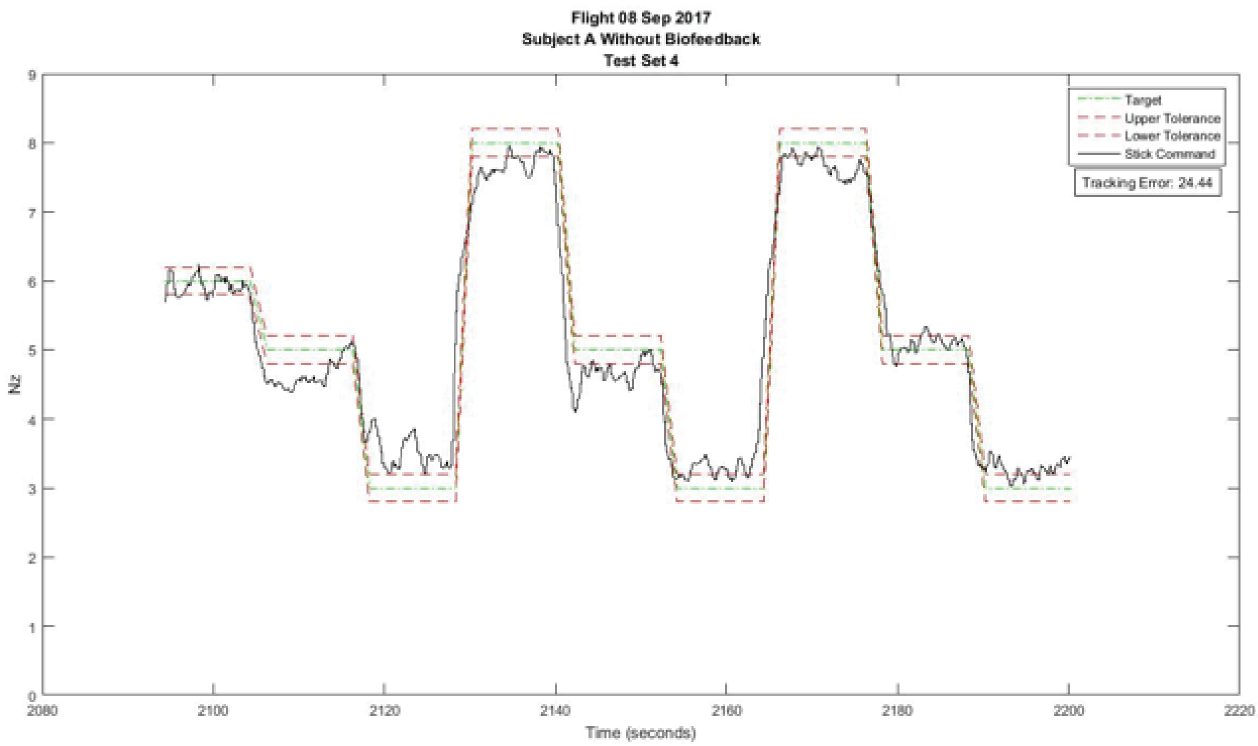


Figure 93: Subject A Phase 4 Without Biofeedback Test Sets 3-4

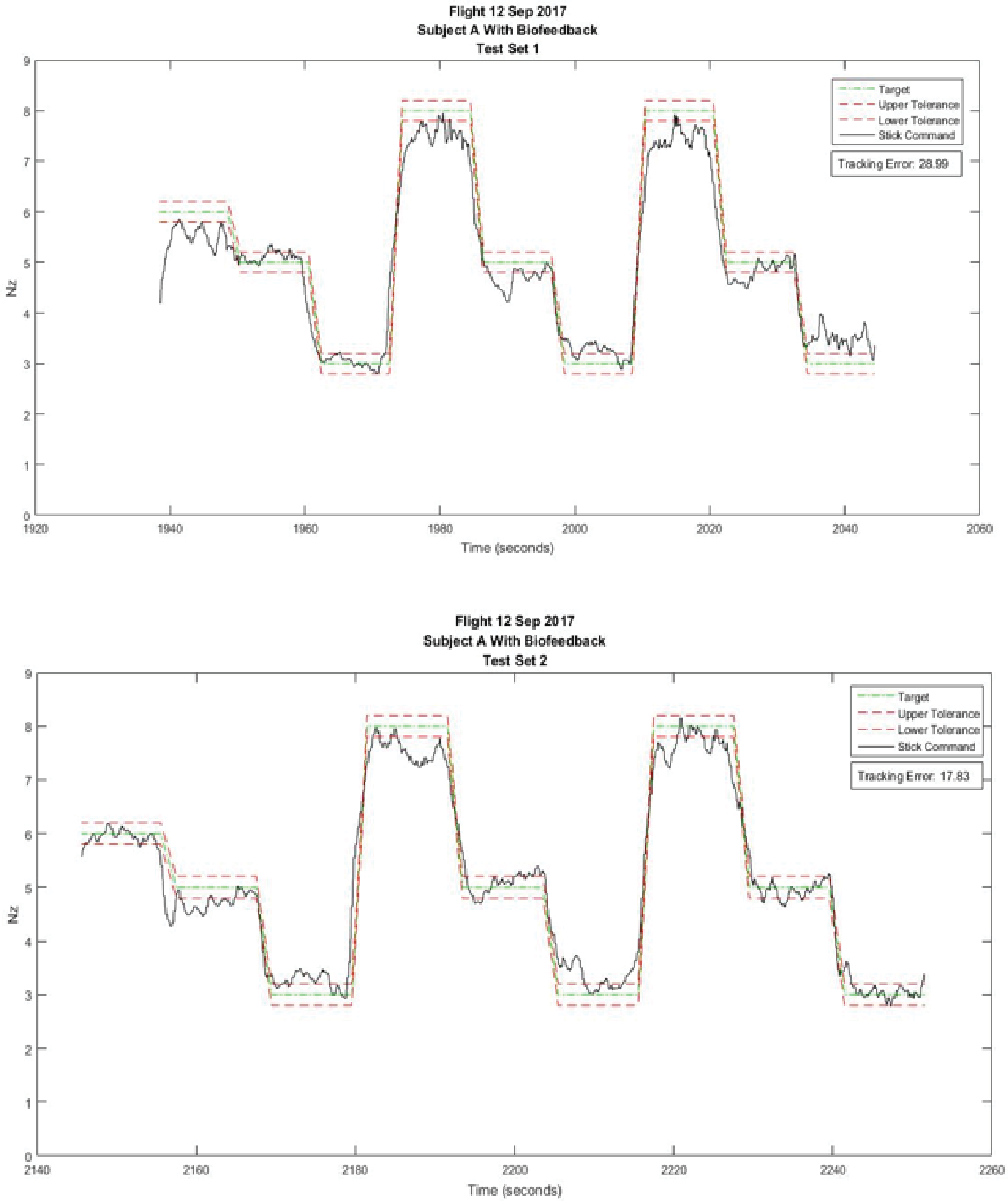
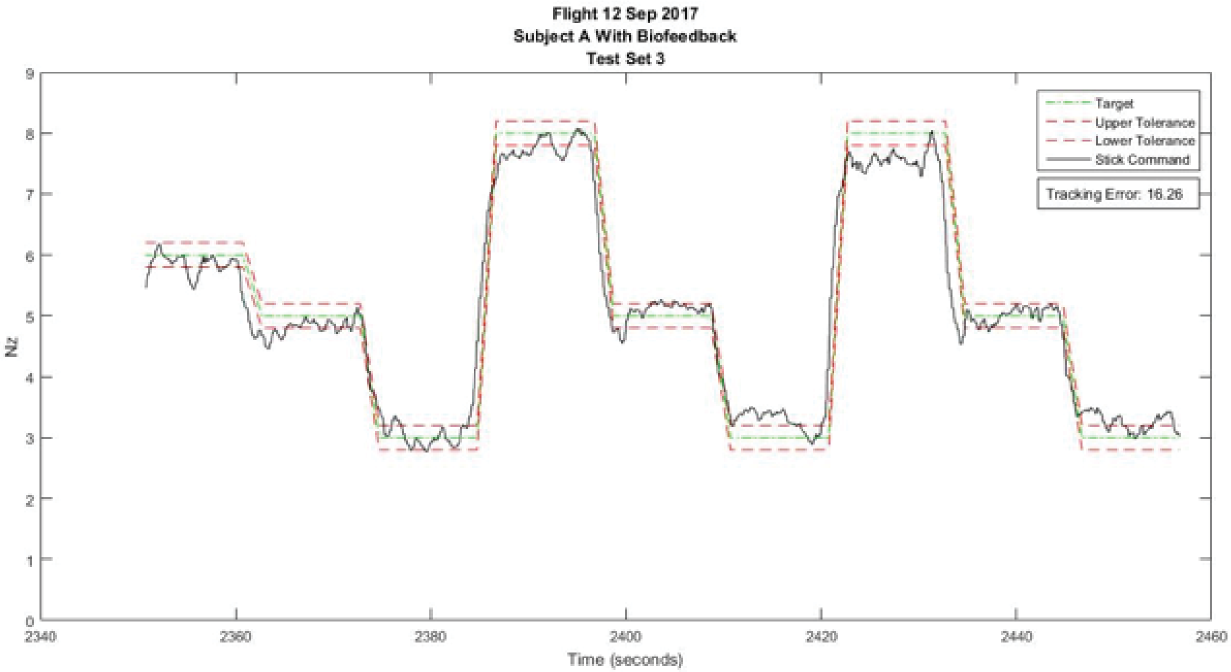


Figure 94: Subject A Phase 4 With Biofeedback Test Sets 1-2



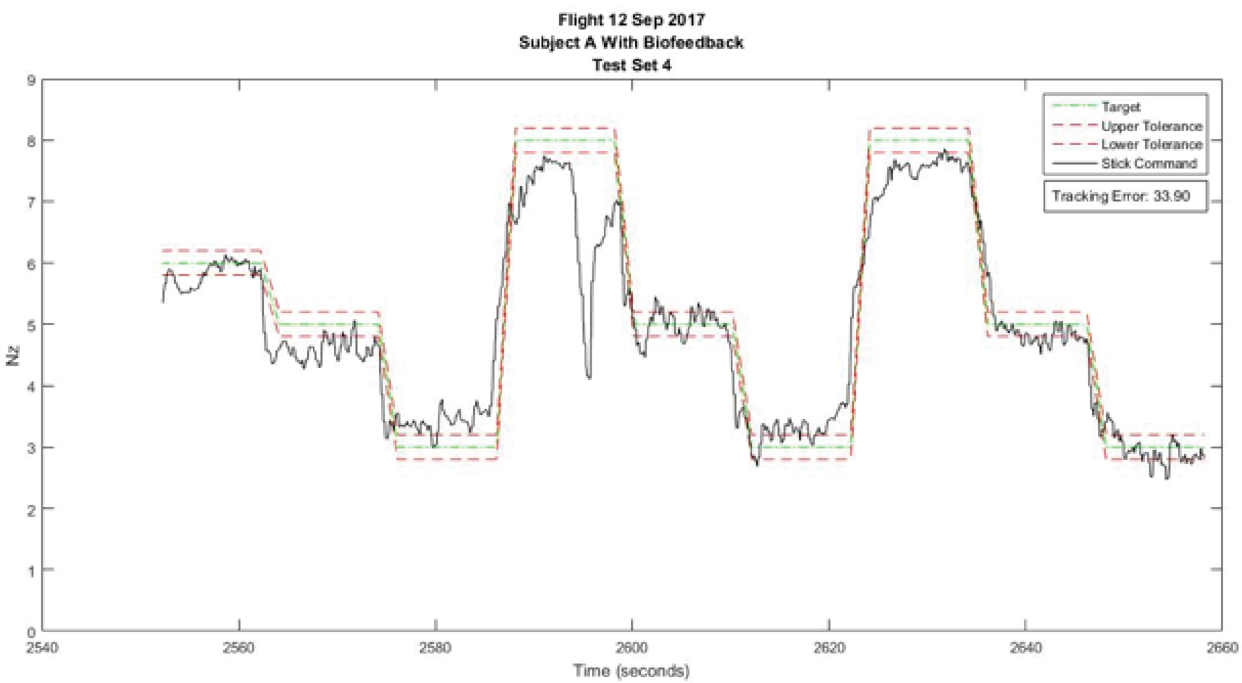
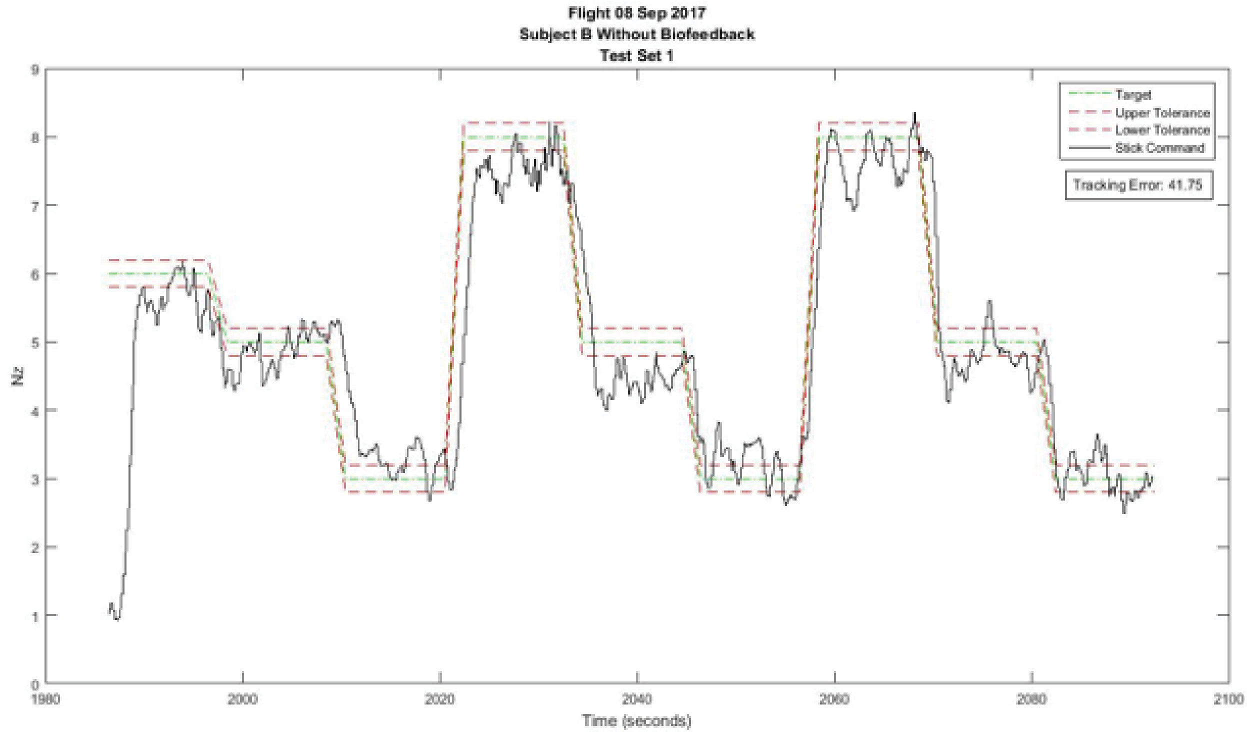


Figure 95: Subject A Phase 4 With Biofeedback Test Sets 3-4



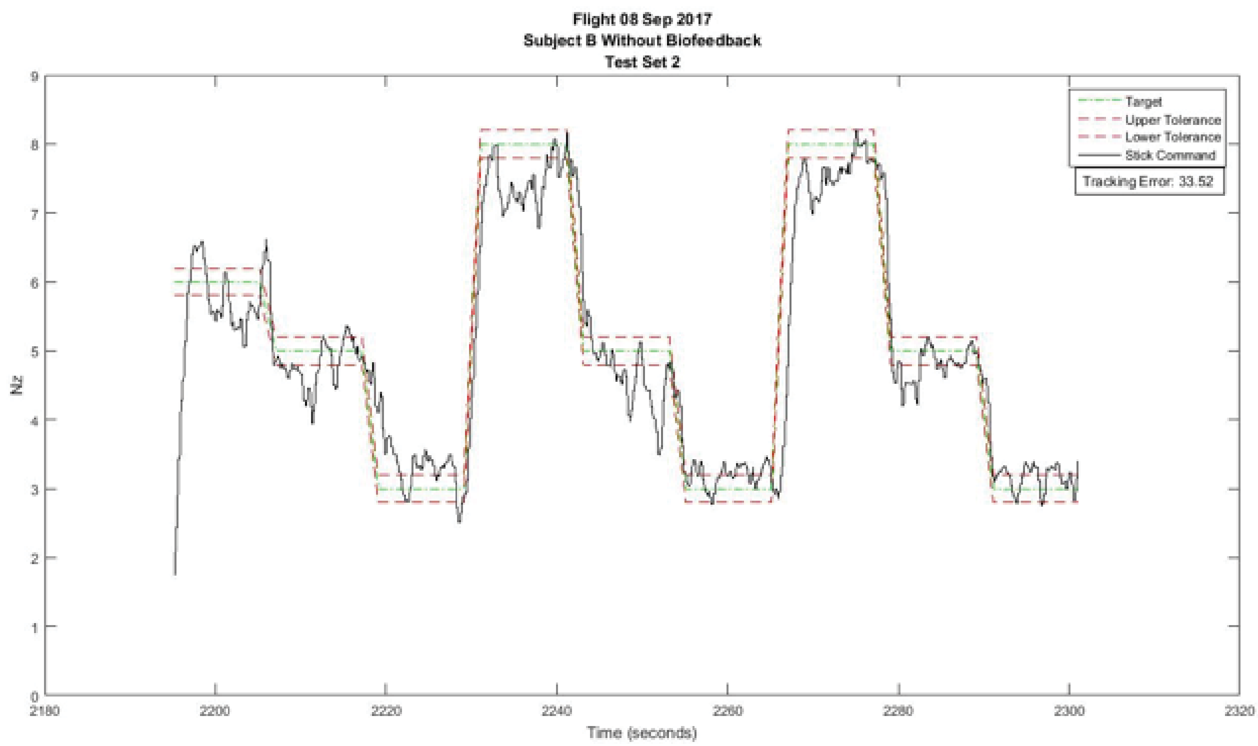
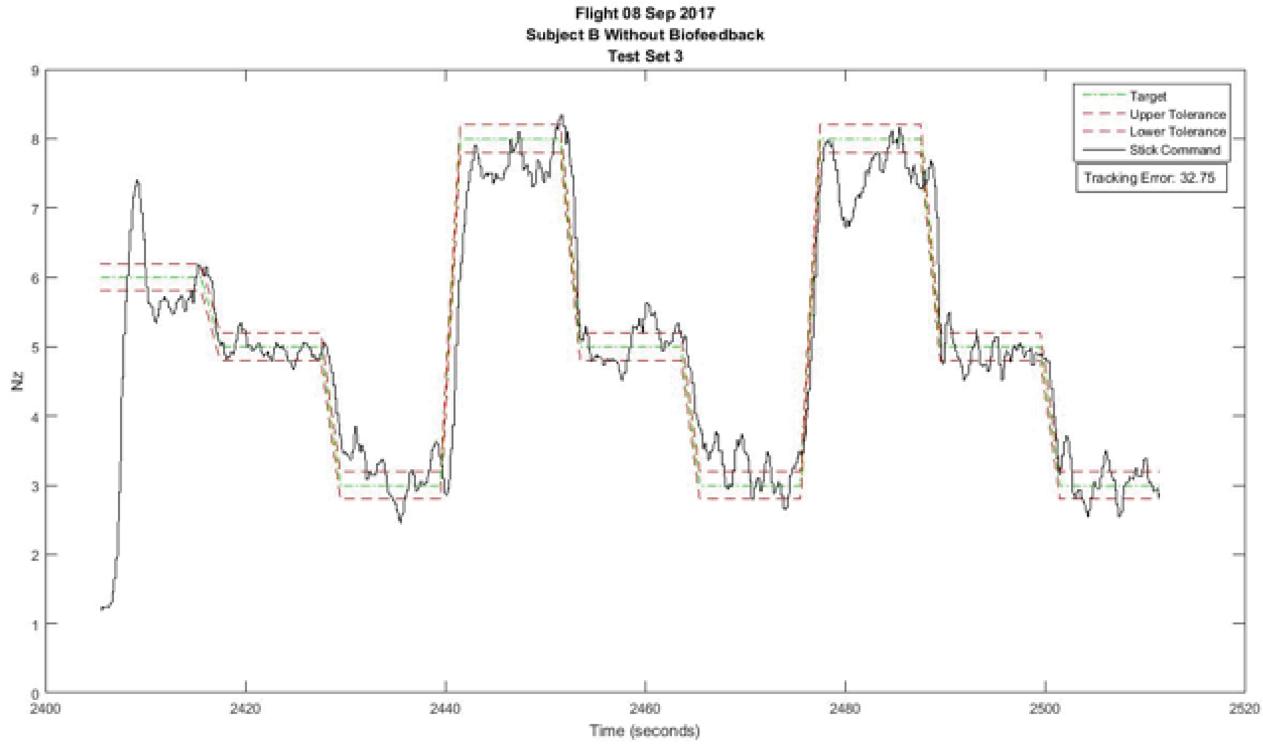


Figure 96: Subject B Phase 4 Without Biofeedback Test Sets 1-2



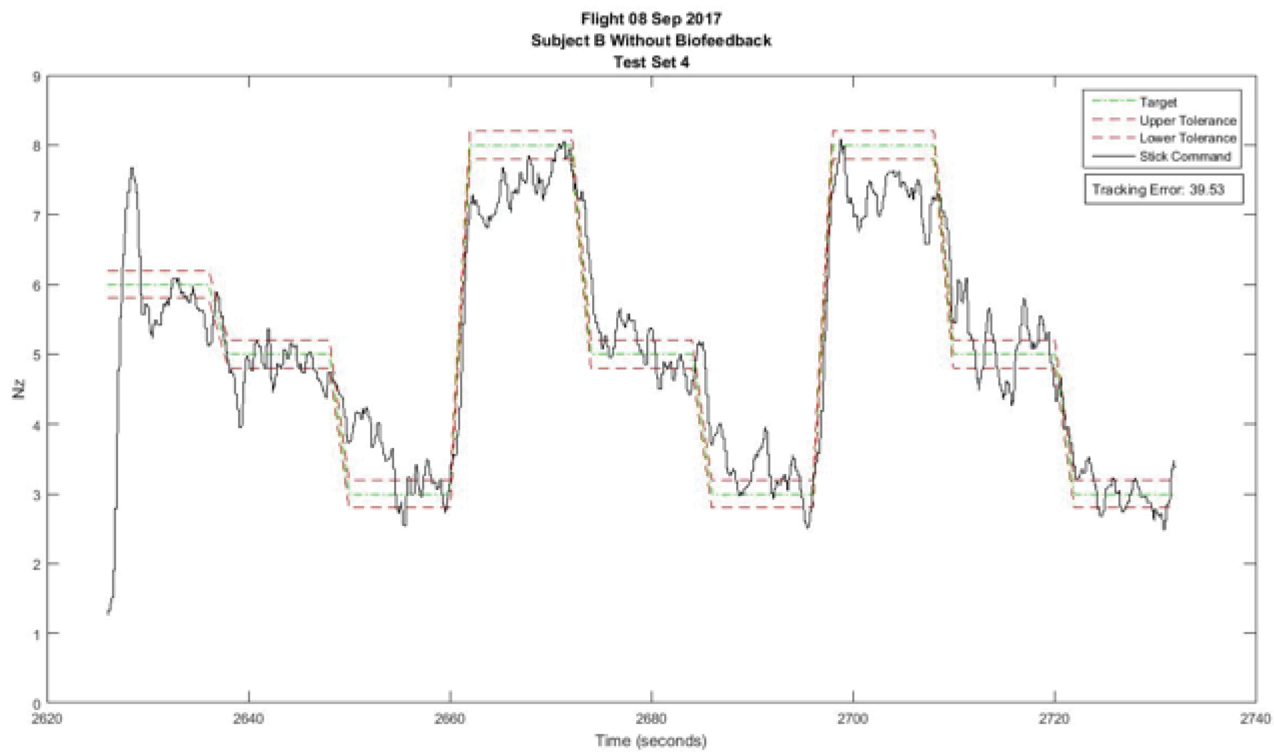
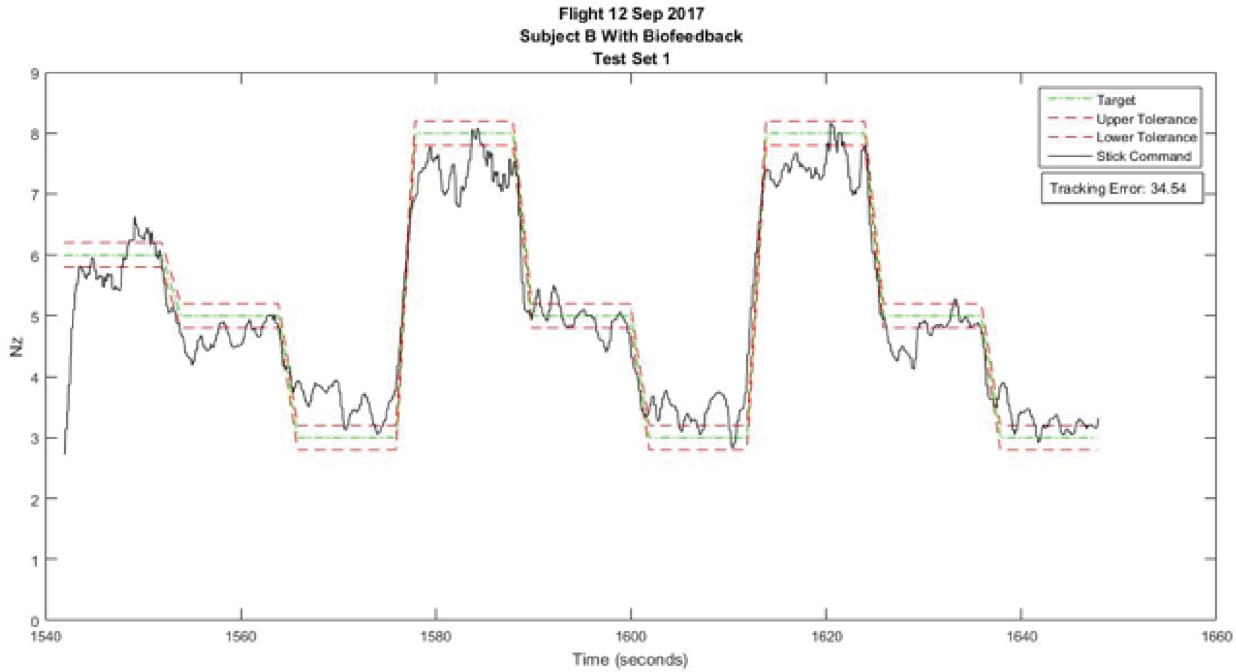


Figure 97: Subject B Phase 4 Without Biofeedback Test Sets 3-4



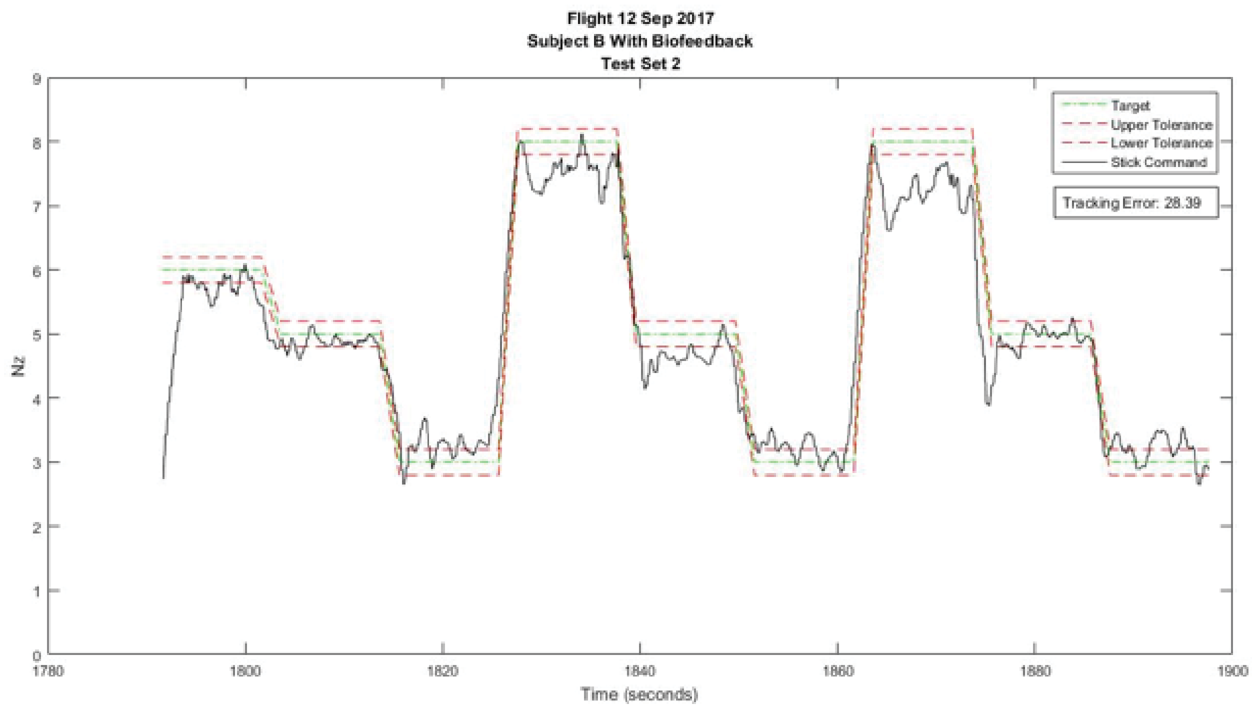


Figure 98: Subject B Phase 4 With Biofeedback Test Sets 1-2

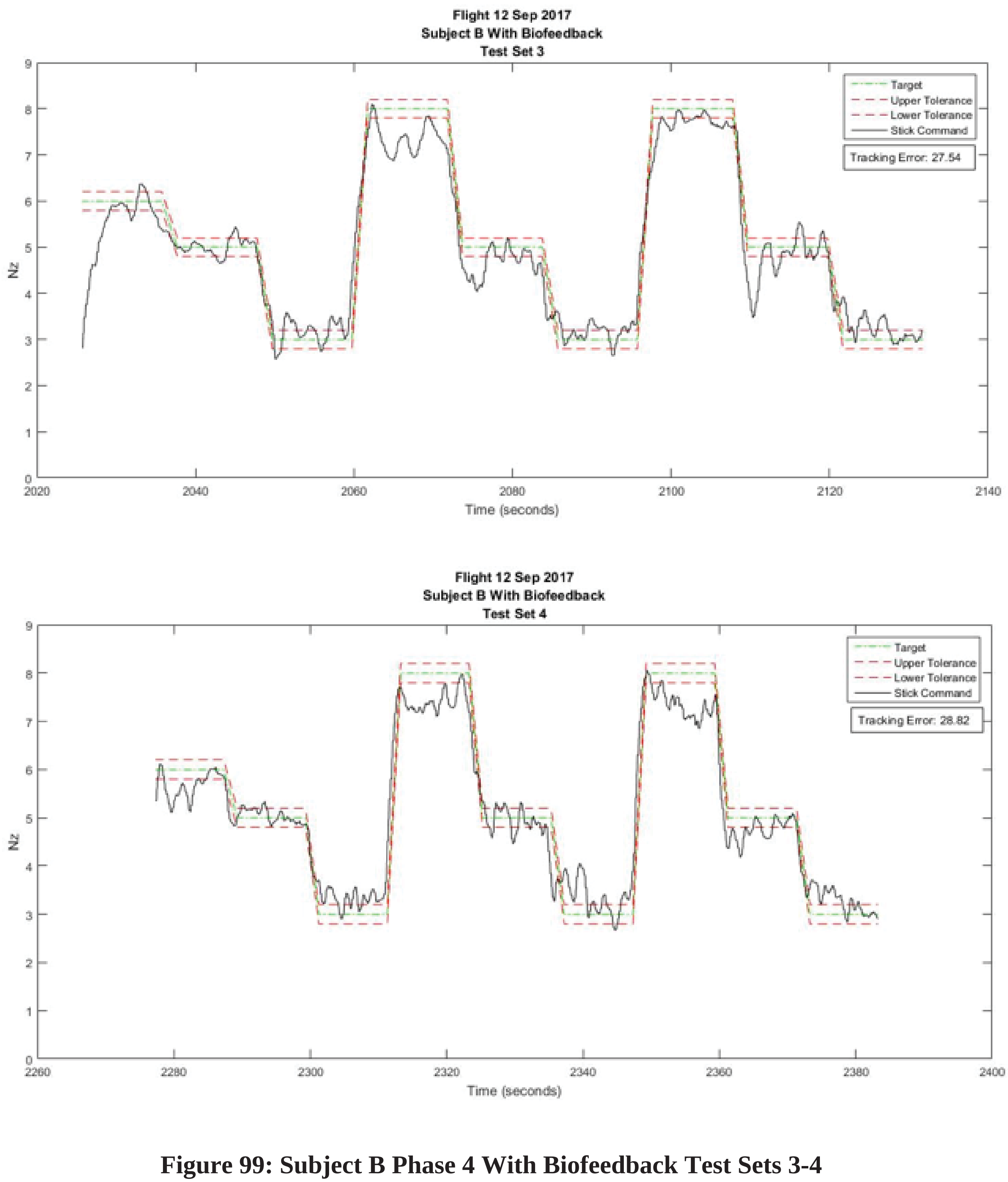


Figure 99: Subject B Phase 4 With Biofeedback Test Sets 3-4

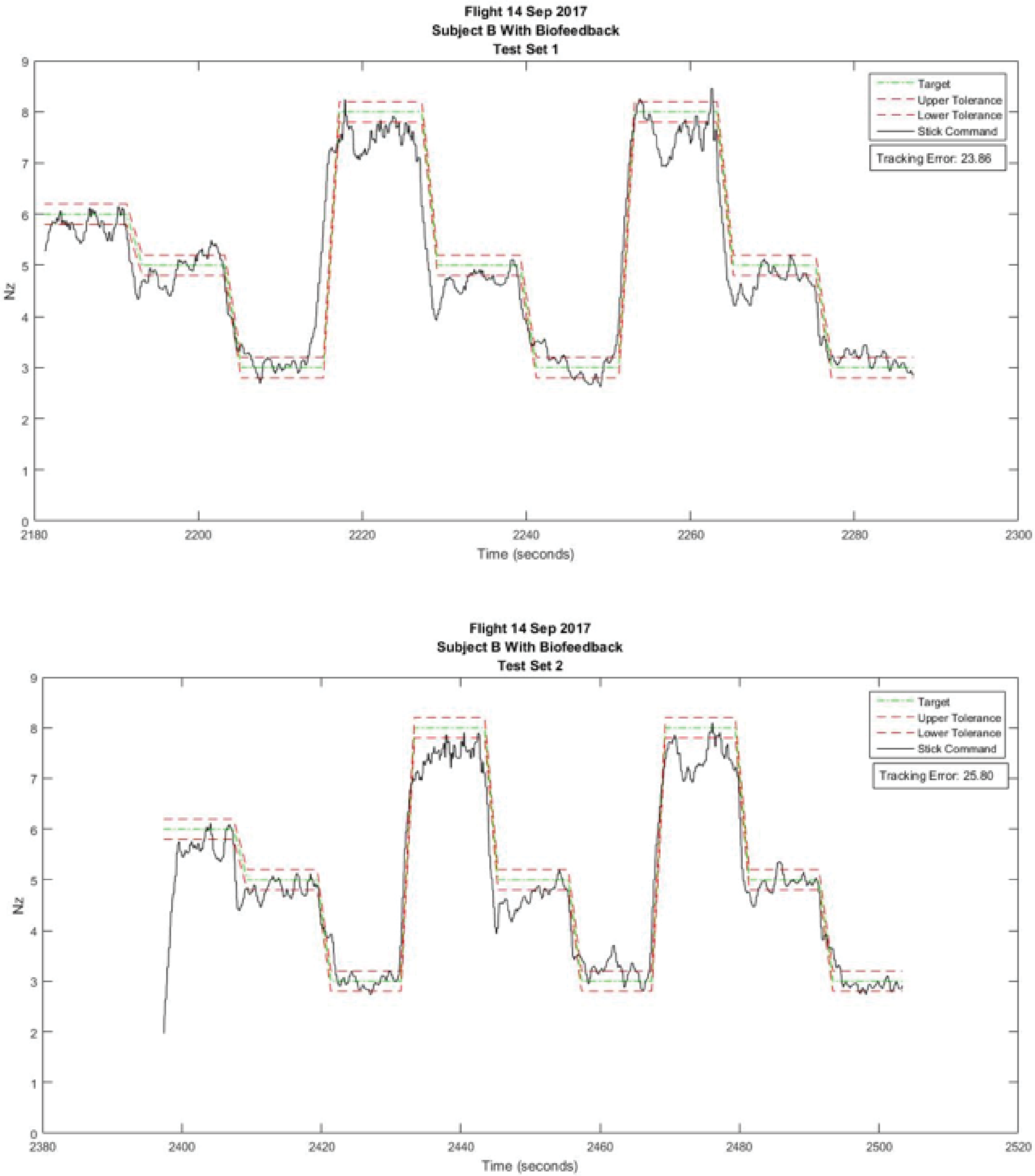
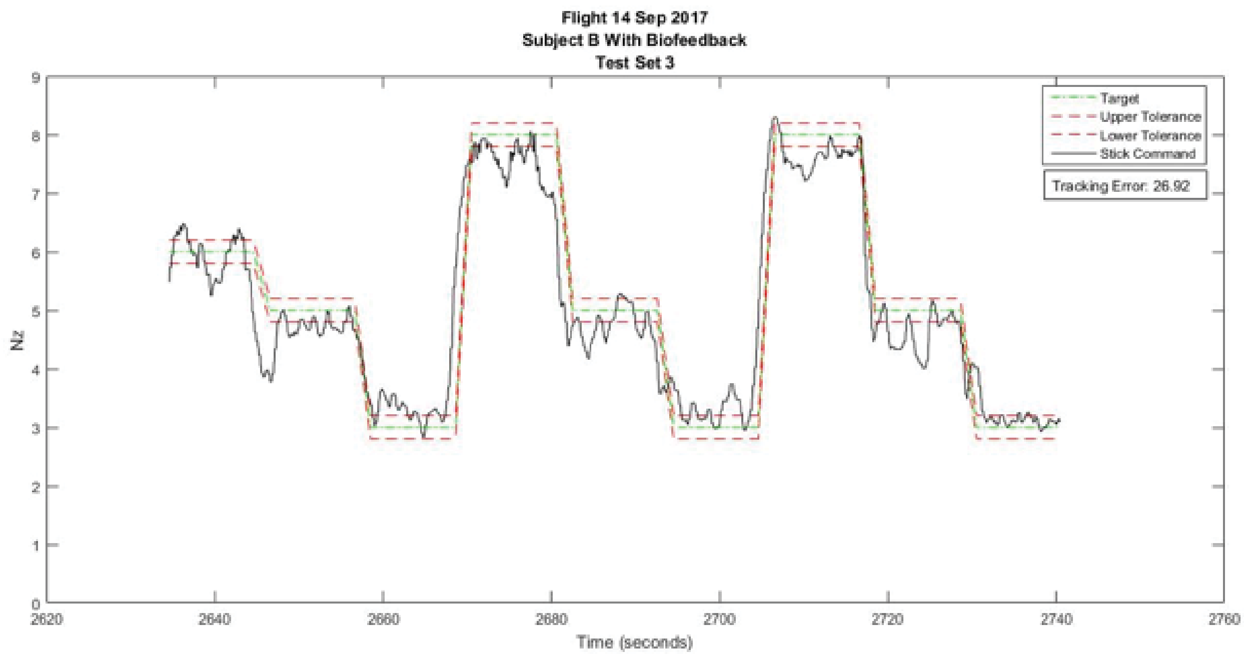


Figure 100: Subject B Phase 4 With Biofeedback Test Sets 1-2



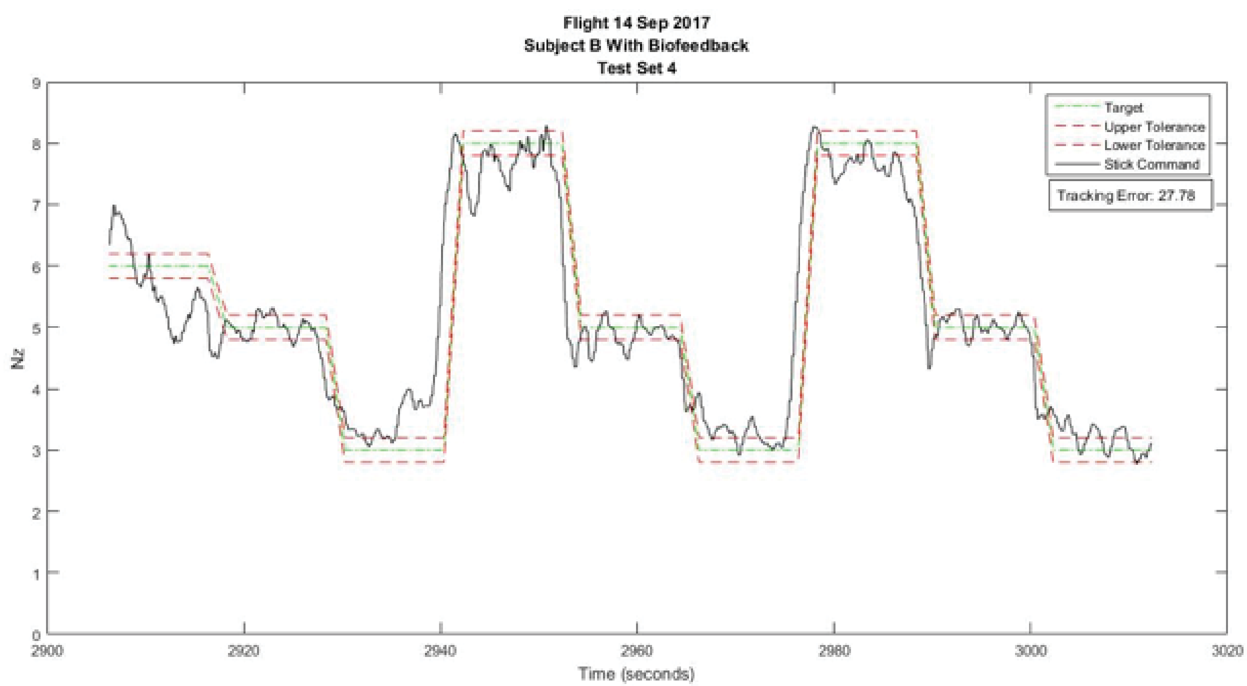
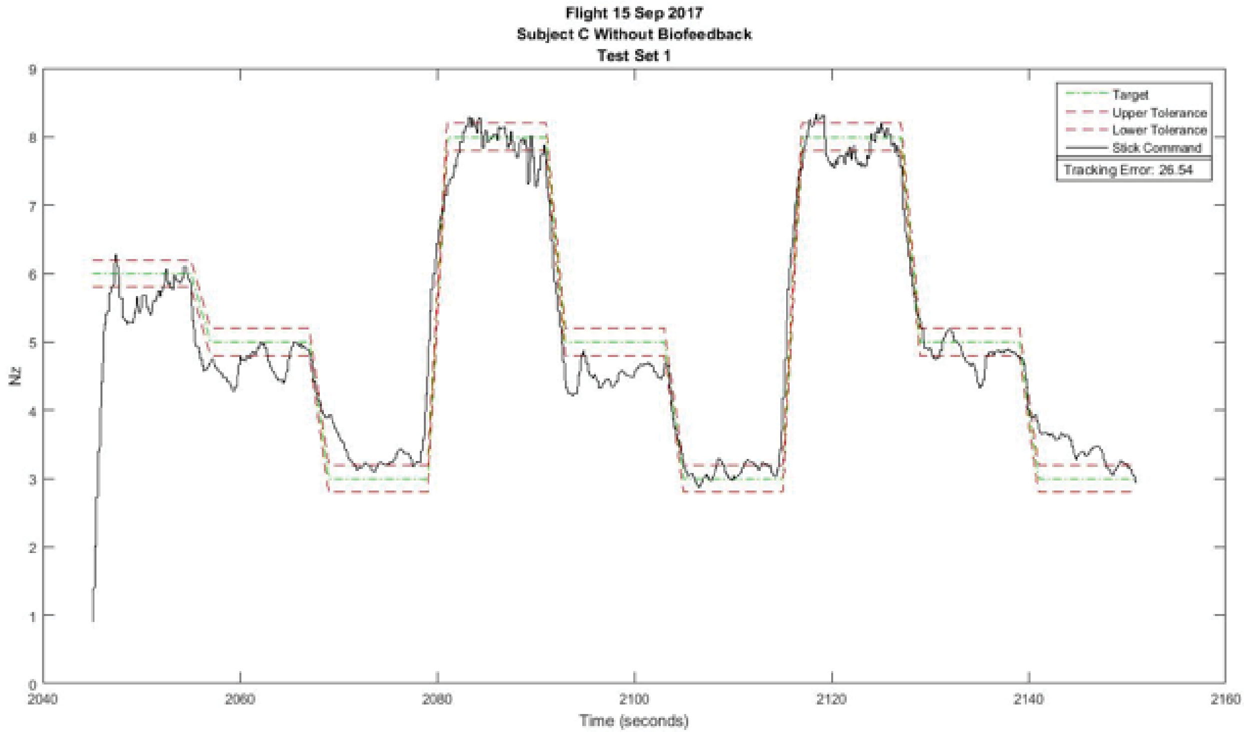


Figure 101: Subject B Phase 4 With Biofeedback Test Sets 3-4



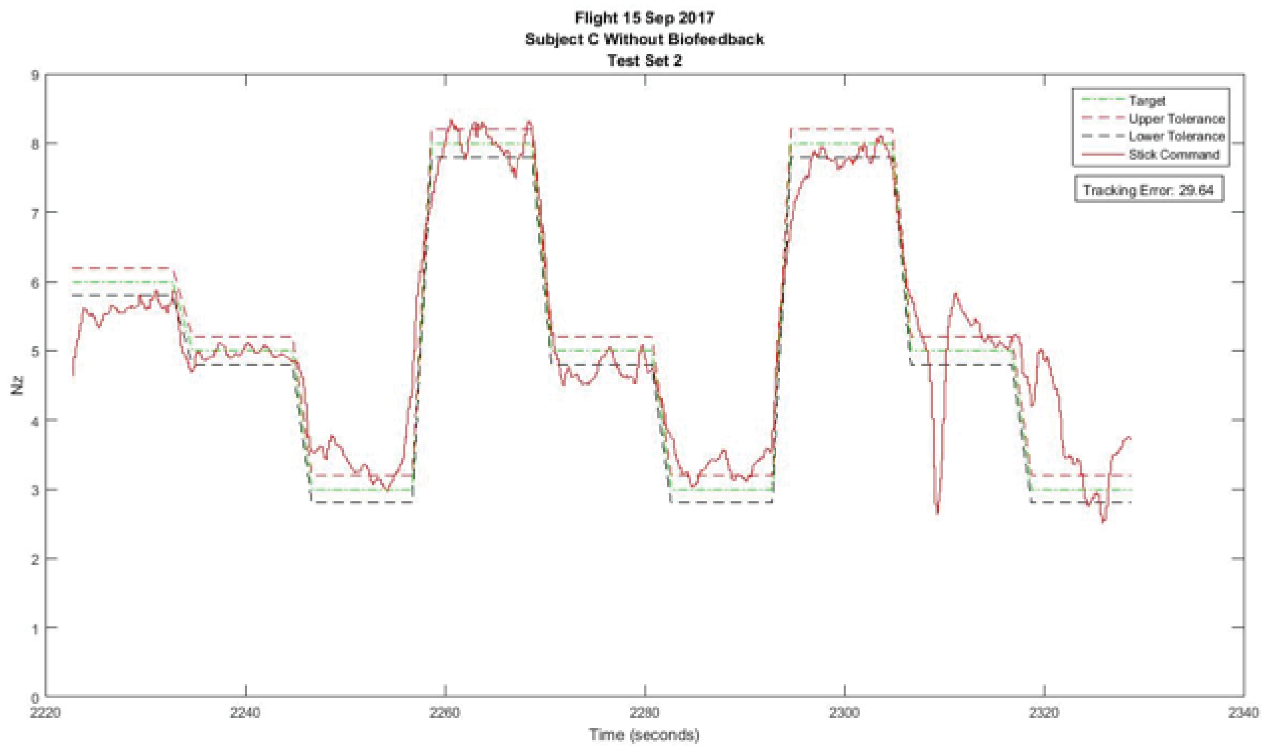
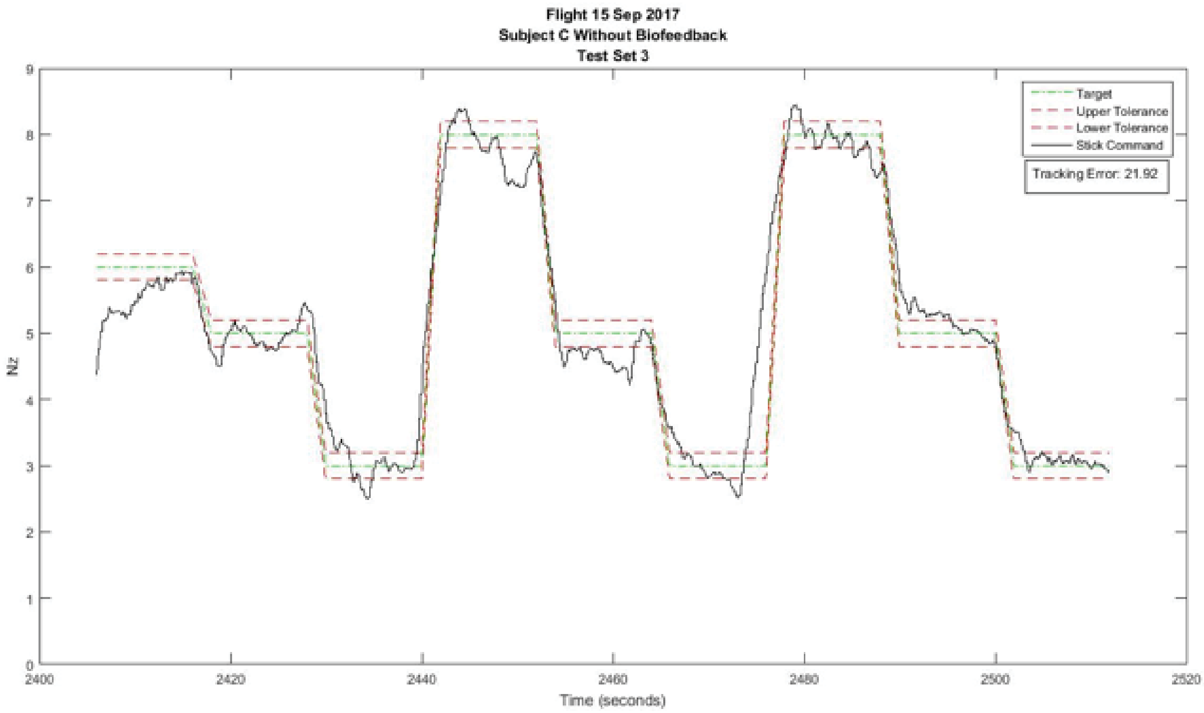


Figure 102: Subject C Phase 4 Without Biofeedback Test Sets 1-2



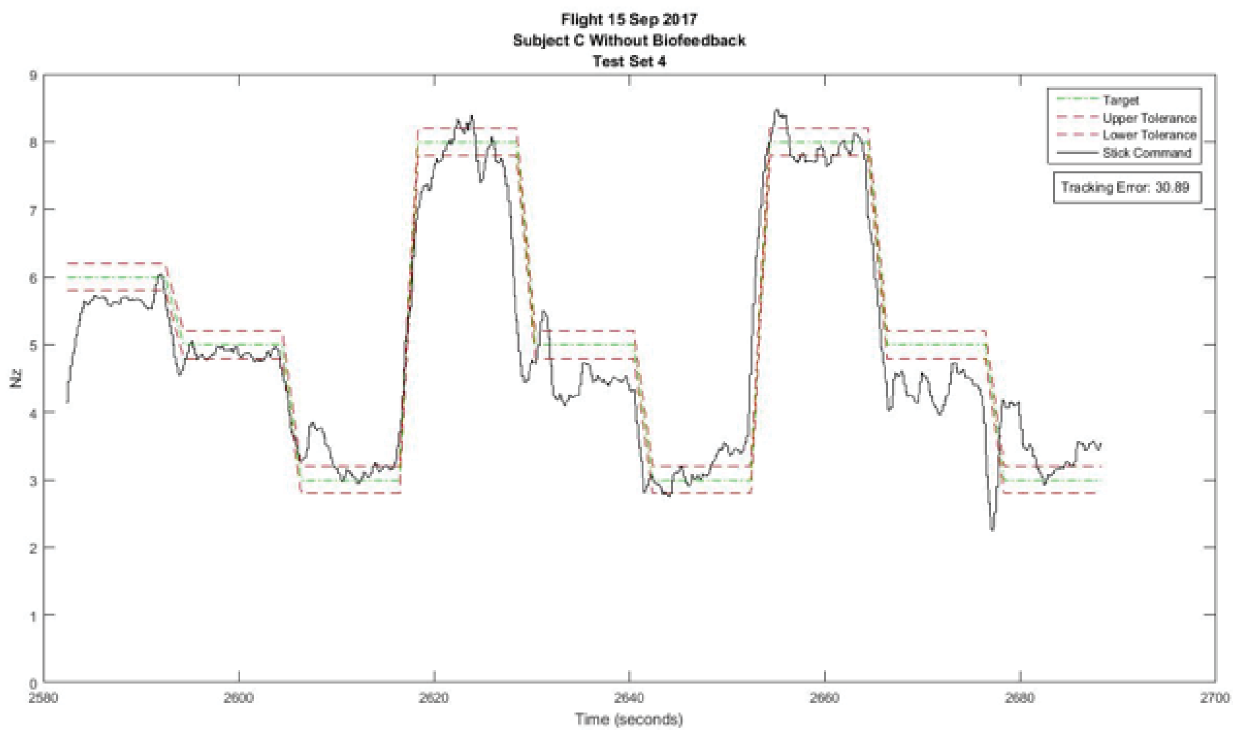
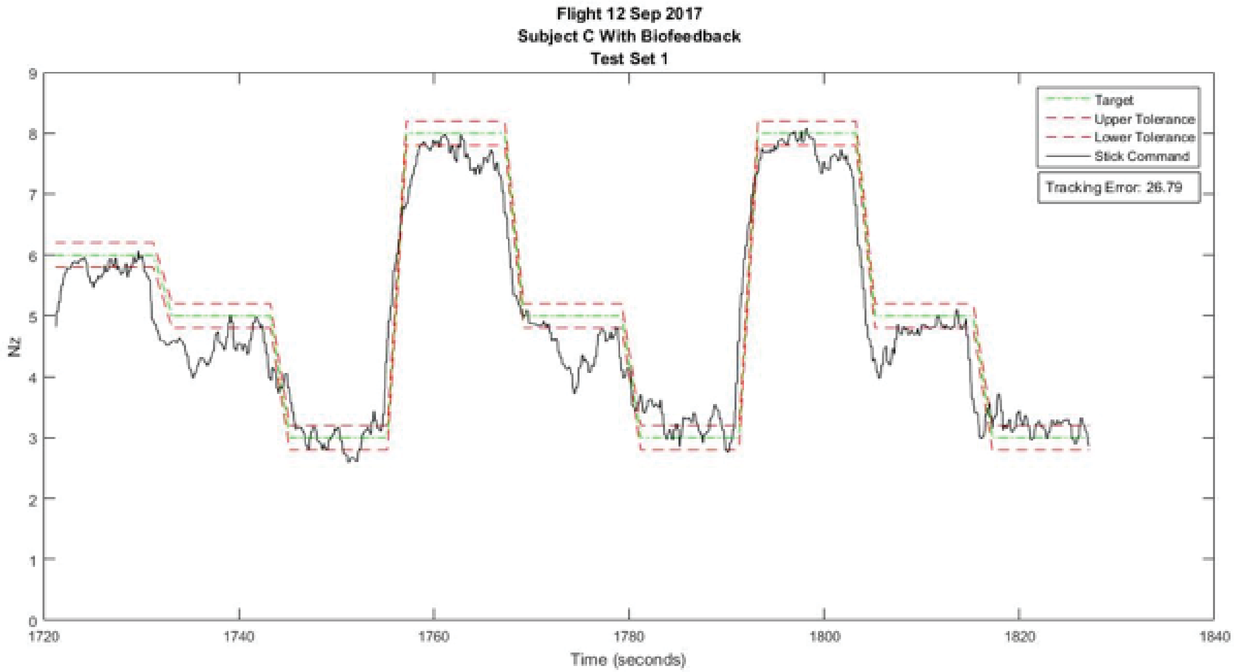


Figure 103: Subject C Phase 4 Without Biofeedback Test Sets 3-4



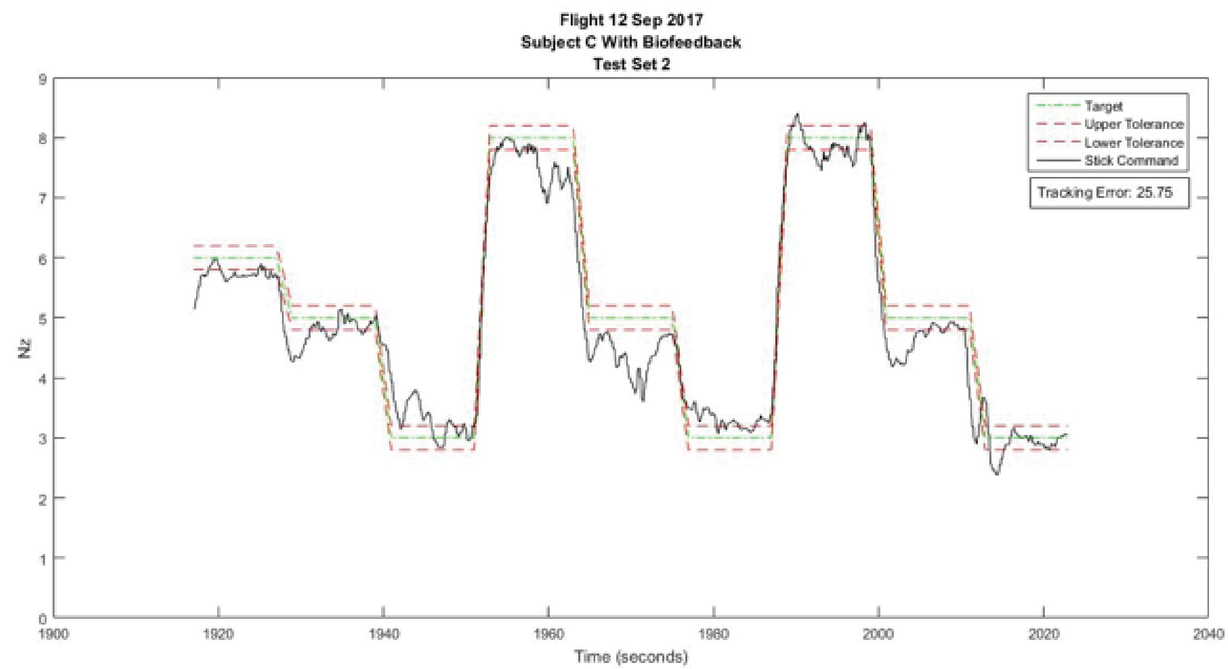
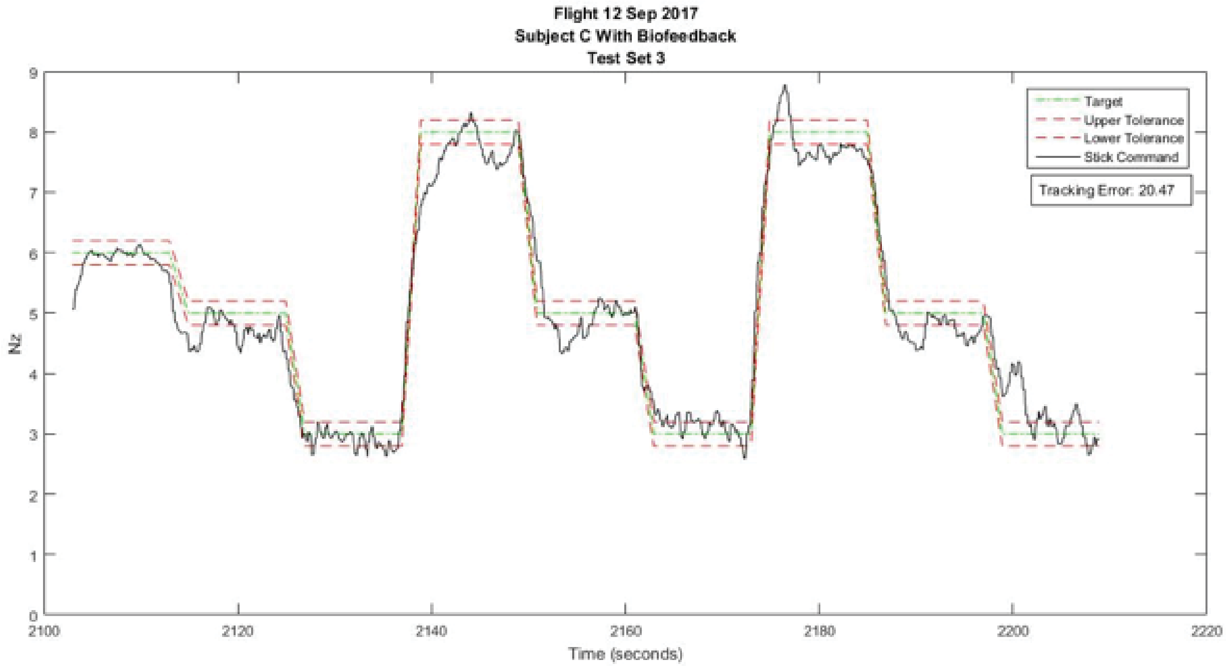


Figure 104: Subject C Phase 4 With Biofeedback Test Sets 1-2



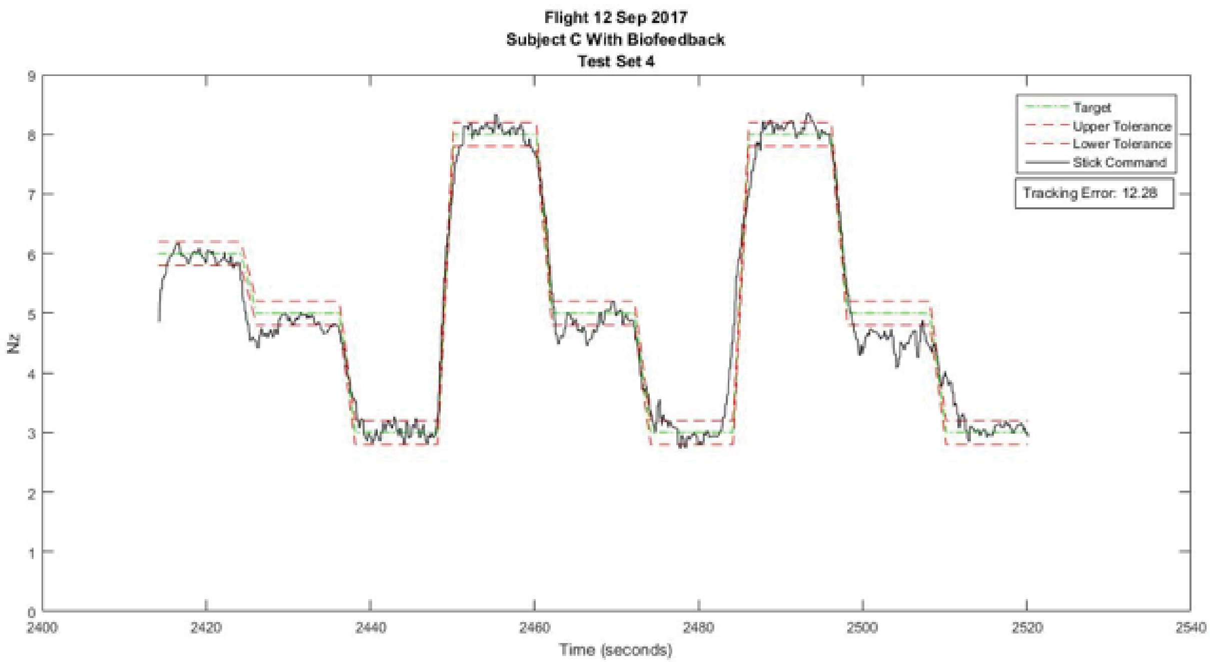


Figure 105: Subject C Phase 4 With Biofeedback Test Sets 3-4

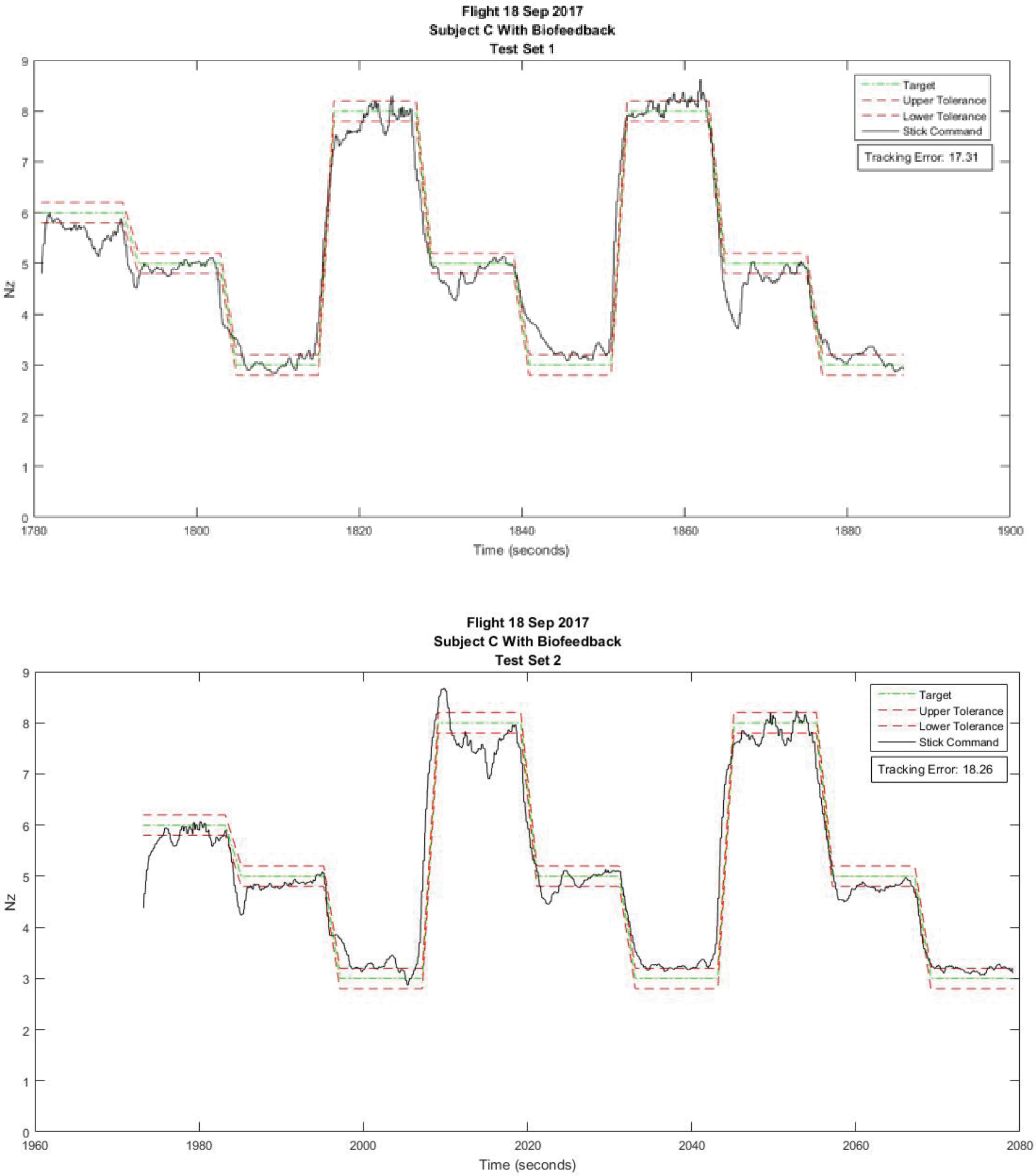
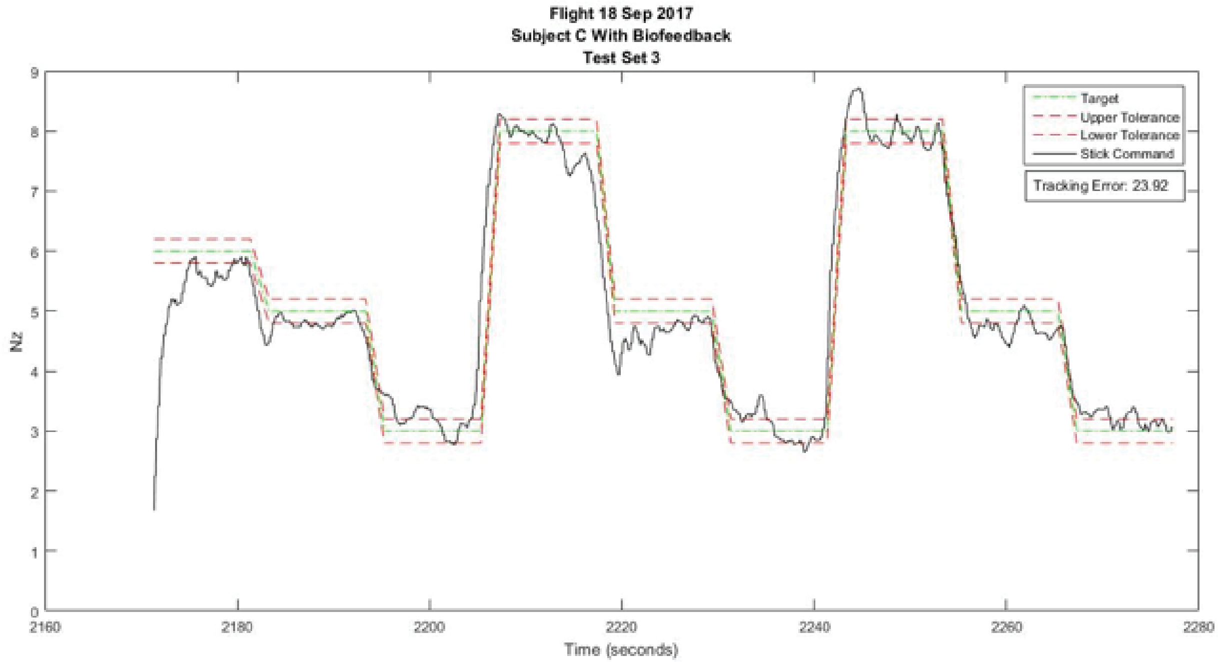


Figure 106: Subject C Phase 4 With Biofeedback Test Sets 1-2



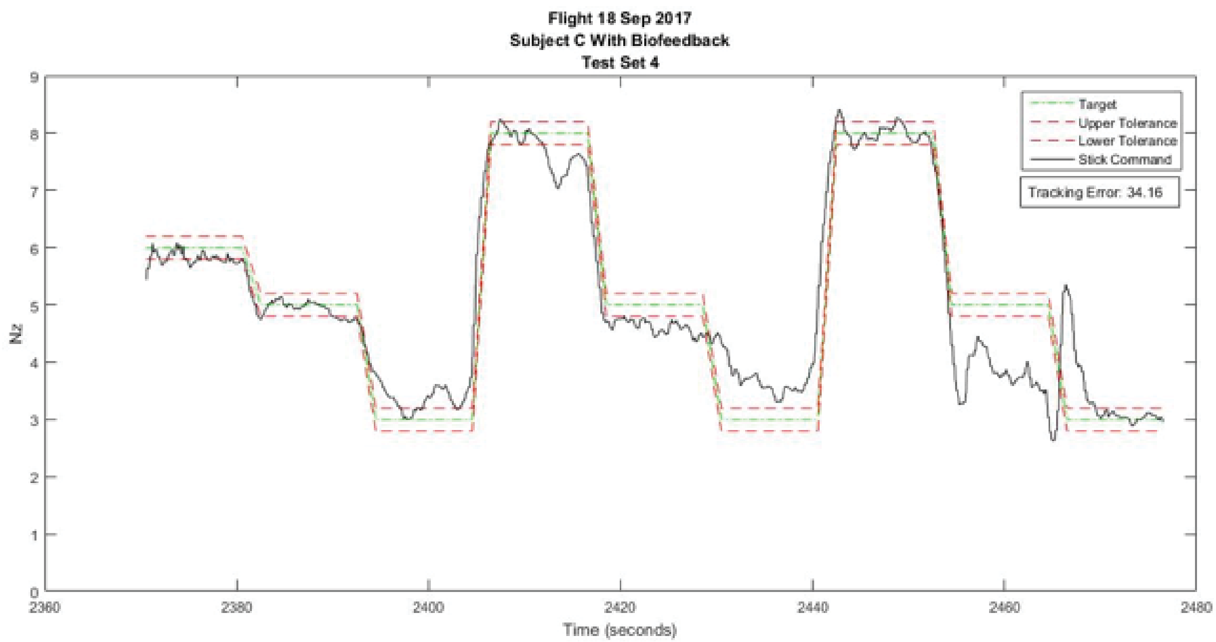


Figure 107: Subject C Phase 4 With Biofeedback Test Sets 3-4

Appendix I – Rating and Evaluation Criteria

Table 19: 412th Test Wing Rating Criteria

How Well Does the System Meet Mission and/or Task Requirements?	Changes Recommended for Improvement	Mission/Task Impact	Descriptor	Rating
Exceeds requirements.	None	None	Excellent	Satisfactory
Meets all or a majority of the requirements.	Negligible changes needed to enhance or improve operational test or field use	Negligible	Good	Satisfactory
Some requirements met; can do the job, but not as well as it could or should.	Minor changes needed to improve operational test or field use	Minor	Adequate	Satisfactory
Minimum level of acceptable capability and/or some noncritical requirements not met.	Moderate changes needed to reduce risk in operational test or field use	Moderate	Borderline	Marginal
One or some of the critical functional requirements were not met.	Substantial changes needed to achieve satisfactory functionality	Substantial	Deficient	Unsatisfactory
A majority or all of the functional requirements were not met.	Major changes required to achieve system functionality	Major	Unacceptable	Unsatisfactory
Mission not safe.	Critical changes mandatory	Critical	Unsafe	Failed

Table 20: 412th Test Wing Six-Point General Purpose Scale

Scale Value	Response Alternatives	Definitions
1	Very Unsatisfactory	Task cannot be performed or the item is unusable or unsafe. Mission/Task not accomplished due to equipment deficiencies or procedural limitations.
2	Unsatisfactory	Major problems encountered. Task accomplished with great difficulty or accomplished poorly. Significant degradation of mission/task accomplishment or accuracy.
3	Marginally Unsatisfactory	Minor problems encountered. Task accomplished with some difficulty. Some degradation of mission/task accomplishment or accuracy.
4	Marginally Satisfactory	The item or task meets its intended purpose with some reservations. Meets minimum requirements to accomplish mission/task.
5	Satisfactory	The item or task meets its intended purpose; it could be improved to make it easier or more efficient.
6	Very Satisfactory	The item or task is fine the way it is; no improvement required.

Table 21: 412th Test Wing Mean Score Evaluation Criteria

Rating	Mean score
Satisfactory	4.5 – 6.0
Marginal	2.5 – 4.4
Unsatisfactory	1.0 – 2.4

Table 22: 412th Test Wing Mean Score Descriptors and Rating

Mean	Descriptor	Rating
Mean equal to 6.0	Excellent	Satisfactory
Mean equal to or between 5.1 and 5.9	Good	Satisfactory
Mean equal to or between 4.5 and 5.0	Adequate	Satisfactory
Mean equal to or between 2.5 and 4.4	Borderline	Marginal
Mean equal to or between 2.0 and 2.4	Deficient	Unsatisfactory
Mean equal to or between 1.1 and 1.9	Unacceptable	Unsatisfactory
Mean equal to 1.0	Unsafe	Failed

Appendix J – GETAC %HRR Display Surveys

SUBJECT A

RATING	FACTOR	DEFINITION
3	Format, Readability	Size, shape, and placement of the biofeedback text and symbology
4	Fit/Comfort	Fit and comfort of the tablet for duration of flight
4	Jitter / Distortion	Amount of symbology and text jitter/distortion
2	Visual Access	Visual angle sufficient to view required information
3	Information	Level of information provided is useful and appropriate
2	Controls	Ease of operation, placement

Comments:

Direct sunlight readability is a problem, barely visible in direct sunlight, which required aircrew to shadow screen to read information. Information provided is very basic, and no recording capability severely restricts data gathering for follow on testing.

Tablet holder is basic, and obscures function buttons on top of tablet, but is comfortable for the duration of the flight. Recommend a hard side holder that tablet snaps into which allows manipulation of tablet buttons.

Tablet GUI is okay for basic information presentation, but location on leg is not useful for immediate and quick checking of information. If system somehow gets out of the program, getting back into the program is extremely difficult. If for some reason the program crashed and you had to restart it, the clickable icons on the touchscreen are so small that without a tablet pen pointer, good luck restarting the program.

Were there any aspects of the mission not covered by these question items that might adversely impact?

Workload?

No [X] Yes [ ] if yes, please comment:

Mission Effectiveness?

No [X] Yes [ ] if yes, please comment:

Flight Safety?

No [X] Yes [ ] if yes, please comment:

SUBJECT B

RATING	FACTOR	DEFINITION
2.7	Format, Readability	Size, shape, and placement of the biofeedback text and symbology
5	Fit/Comfort	Fit and comfort of the tablet for duration of flight
3.3	Jitter / Distortion	Amount of symbology and text jitter/distortion
2.7	Visual Access	Visual angle sufficient to view required information
3	Information	Level of information provided is useful and appropriate
2.7	Controls	Ease of operation, placement

Comments:

Glare from the sun impedes ability for aircrew to read information from the screen. Additionally, issue is exacerbated by the fact the font is hard to read along with interpretation of my biofeedback due to noisy readout of data.

No issues with fitment of tablet holder. However, cumbersome getting into aircraft with wires and leads hanging out everywhere. Recommend better consolidation of leads and wires.

Heads down time require reading and interpreting data readouts adversely affected flying performance. Would regularly have to correct speed or altitude deviations after continuous periods looking at the screen.

Noticed a considerable increase in workload trying to interpret data during flying ops compared to centrifuge ops

Were there any aspects of the mission not covered by these question items that might adversely impact?

Workload?

No [X] Yes [ ] if yes, please comment:

Mission Effectiveness?

No [X] Yes [ ] if yes, please comment:

Flight Safety?

No [X] Yes [ ] if yes, please comment:

SUBJECT C

RATING	FACTOR	DEFINITION
2.5	Format, Readability	Size, shape, and placement of the biofeedback text and symbology
3	Fit/Comfort	Fit and comfort of the tablet for duration of flight
2.5	Jitter / Distortion	Amount of symbology and text jitter/distortion
3	Visual Access	Visual angle sufficient to view required information
3	Information	Level of information provided is useful and appropriate
1.5	Controls	Ease of operation, placement

Comments:

Format/Readability:

- %HRR displayed! Improvement from previous version at centrifuge. Also, incorporated basic 0-100% scale. Info could be bigger and more readable
  R1: Further incorporating MIL-STD human factors requirements into display.
- Raw heart rate number displayed with no scale/graph/color display usage. Recommend incorporating MIL-STD human factors requirements into display.

Fit/Comfort:

- Nothing changed since centrifuge. Leg mounted tablet with holster acceptable, but not ideal.
- R2: future incorporation into existing cockpit displays or added display mounted to aircraft. Leg mounted was bulky for aircraft walkout/preflight.
- For initial concept a leg mounted tablet with holster was acceptable, but not ideal. Recommend future incorporation into existing cockpit displays or added display mounted to aircraft. Leg mounted was bulky walking to/from centrifuge.

Jitter/Distortion:

- %HRR values more stable than centrifuge, but occasionally still jumping from actual %HHR value to bogus values greater than 100%. Required looking for multiple seconds to ensure reading truth value.
- Heart Rate values were not stable and/or easy to read. Values jumping from actual HR value to 255 (bogus value).

Visual Access:

- R3: Incorporate information into existing cockpit displays and/or added mounted displays in accordance with current MIL-STD guidance for viewing angles, colors, contrast, etc.
- For initial hardware in-flight concept, information was viewable, but for future implementation recommend incorporating information into existing cockpit displays and/or in accordance with current MIL-STD guidance for viewing angles, colors, contrast, etc.

Information:

- Information displayed heart rate values, which was not in accordance with expected final product. We expected and planned for %HRR values on a 1-100% scale. Hardware is still in early development stages, which caused display crashing issues with %HRR.
- Information displayed %HRR values. Big improvement from centrifuge to flight
- Raw heart rate and breaths per minute were not displayed

Controls:

- Function and usability was very poor. Very specific steps/process was required to get display on and working without crashing. If deviated, display froze and info not available. Display needs to be very easy to use and manipulate controls/options for future in-flight cockpit implementation.

Were there any aspects of the mission not covered by these question items that might adversely impact?

1. Workload?

   No [X] Yes [ ] if yes, please comment:

2. Mission Effectiveness?

   No [ ] Yes [X] if yes, please comment:

   More difficult cross check with leg mounted. Tough to scan information on tablet on leg vs. more forward mounted for better scan. Ambient light in cockpit was also minor issue. Sometimes required shielding sunlight with hand to see display since couldn't adjust brightness enough.

3. Flight Safety?

   No [ ] Yes [X] if yes, please comment:

   Added weight during aircraft egress. Emergency ground egress might be tougher with bulky leg mounted tablet. Aircraft ejection potentially more dangerous with leg mounted tablet

SUBJECT D

RATING	FACTOR	DEFINITION
2	Format, Readability	Size, shape, and placement of the biofeedback text and symbology
4	Fit/Comfort	Fit and comfort of the tablet for duration of flight
4	Jitter / Distortion	Amount of symbology and text jitter/distortion
2	Visual Access	Visual angle sufficient to view required information
3	Information	Level of information provided is useful and appropriate
1	Controls	Ease of operation, placement

Comments:

Format/Readability:
- %HRR information difficult to read due to font size
- The key information (%HRR) is buried in the middle of the screen with a lot of other information not relevant to the user. This cause distraction and difficultly to easily and quickly locate the required information.

Fit/Comfort:
- A lot of leads hanging off the GTAC.
- Takes a lot of time and specific training to fit to subject.

Jitter/Distortion:
- Noisy values make it difficult to interpret
- Stuck on arbitrary number during centrifuge trials – not useful

Visual Access:
- Requires look down – not an issue in the centrifuge but may be a factor in the aircraft.

Information:
- Information displayed in the GTAC was not the required %HRR during centrifuge trials.
- Had to advise actual heart rate to control, then they would provide a %HRR from test subject specific generated table. This added time and potentially corrupted test data.

Controls:
- Difficult to use without specialized training
- Suspect significant increase in workload if required to modify controls while airborne

Were there any aspects of the mission not covered by these question items that might adversely impact?

Workload?

No [X] Yes [ ] if yes, please comment:

Mission Effectiveness?

No [ ] Yes [X] if yes, please comment: The inability to provide %HRR will reduce the ability to gather data during flight test in September.

Flight Safety?

No [X] Yes [ ] if yes, please comment:

SUBJECT E

RATING	FACTOR	DEFINITION
2	Format, Readability	Size, shape, and placement of the biofeedback text and symbology
6	Fit/Comfort	Fit and comfort of the tablet for duration of flight
5	Jitter / Distortion	Amount of symbology and text jitter/distortion
3	Visual Access	Visual angle sufficient to view required information
4	Information	Level of information provided is useful and appropriate
2	Controls	Ease of operation, placement

Comments:

Format/Readability:

- Heart rate is difficult to read due to font size

Fit/Comfort:

- Fits well on thigh with not movement or restraining issues.
- Tablet holds well in plastic pouch

Jitter/Distortion:

- Hard to determine what the actually heart rate value is due to noisy readout of data

Visual Access:

- Not in field of view, sometimes difficult to interpret data

Information:

- Was not given the correct information during centrifuge trials. Heart rate versus the required %HRR as per test plan

Controls:

- Was a set and forget, meaning the AFE guy would set it and I would have no understanding of how to operate it apart from looking at the screen.

Were there any aspects of the mission not covered by these question items that might adversely impact?

Workload?

No [X] Yes [ ] if yes, please comment:

Mission Effectiveness?

No [ ] Yes [X] if yes, please comment:

Was showing heart rate instead of %HRR – this should be fixed prior to flight test

Flight Safety?

No [X] Yes [ ] if yes, please comment:

AFE 1

RATING	FACTOR	DEFINITION
5	Format, Readability	Size, shape, and placement of the biofeedback text and symbology
5	Fit/Comfort	Fit and comfort of the tablet for duration of flight
4	Jitter / Distortion	Amount of symbology and text jitter/distortion
4	Visual Access	Visual angle sufficient to view required information
6	Information	Level of information provided is useful and appropriate
4	Controls	Ease of operation, placement

Comments:
Numerous usability, connectivity, and integration with AFE equipment fixes were needed and accomplished during the course of the HAVE HOPE Project which vastly improved the final few flight executions. The GETAC tablet is larger and heavier than other like devices that could have been better to wear for flight test (IPAD with the flight approved “FlyBoys” Kneepad). GETAC Holster modifications for security to the ATAGs G-Suit were needed on the holster straps and case to hold in place due to weight and bulk. Not being able to lock the touch screen for unavoidable touching during cockpit operations presented challenges to prevent uninterrupted viewing during flight. Software display fixes (hide taskbar, maximize biofeedback app, eliminate all notifications, and turn off all time outs, and device sleep settings) were incorporated during project execution. A dimly lit screen display for viewing during flight in sunlight filled cockpit also presented an early challenge, but was improved by maximizing devices lighting/brightness settings and disengaging the backlit auto sensor. On the ECG box containing the motherboard circuitry, the USB connectivity ports were not exactly as flush to the surface as they needed to be. It was necessary to cut away areas around the port, and tape USB connectors down to prevent cable flexing hardware disconnects during aircraft walk around, ladder/cockpit access, and movements in flight. Software controls were relatively easy. Pilots were able to perform Biofeedback tool software app re-execution if needed in the cockpit on the ground, but not during flight due to difficulty in performing a device reset by a pin insertion or by removing a battery to reset. Visual display angles were very acceptable, and I’m not aware of any symbology and or text jitter / distortion being reported by any of the HAVE HOPE flight test execution pilots. The level of Biofeedback information was useful, and appropriate to satisfy the requirements of the flight test data parameters to my knowledge.

Were there any aspects of the mission not covered by these question items that might adversely impact?

1. Workload?

No [ ] Yes [X] if yes, please comment:
Biofeedback software app related only. There needs to be factors and ratings addressed which include Biofeedback tool/device and Control Box aircrew flight gear integration, hardware connectivity issues, and hardware power/battery drain and durations. These added factors when related issues did come up, proved to cost time and added workloads during AFE prefights, and step times, and cockpit preflight times.

2. Mission Effectiveness?

No [ ] Yes [X] if yes, please comment:
Biofeedback software app related only. There needs to be factors and ratings addressed which include Biofeedback tool/device and Control Box aircrew flight gear integration, hardware connectivity issues, and hardware power/battery drain and durations, all of which could and did cost in-effective missions to occur.

3. Flight Safety?

No [ ] Yes [X] if yes, please comment:

All the factors listed above were Biofeedback software app related only. There needs to be factors and ratings addressed which include Biofeedback tool/hardware device and Control Box aircrew flight gear integration, which in this case posed post ejection challenges for flight safety which needed to be worked out.

AFE 2

RATING	FACTOR	DEFINITION
5	Format, Readability	Size, shape, and placement of the biofeedback text and symbology
5	Fit/Comfort	Fit and comfort of the tablet for duration of flight
4	Jitter / Distortion	Amount of symbology and text jitter/distortion
4	Visual Access	Visual angle sufficient to view required information
6	Information	Level of information provided is useful and appropriate
4	Controls	Ease of operation, placement
Comments: There were constant issues with connectivity during the test in the chamber. The tablet is bulky and heavier than some other tablets that could possibly be used. The holster used was okay but I know some aircrew have better kneepads out there that would be more suitable.		

Were there any aspects of the mission not covered by these question items that might adversely impact?

Workload?

No [X] Yes [ ] if yes, please comment:

Mission Effectiveness?

No [X] Yes [ ] if yes, please comment:

Flight Safety?

No [X] Yes [ ] if yes, please comment:

Appendix K – AMPSS 3.0 Surveys

AFE 1

AMPSS 3.0 AIRCREW SURVEY

Use the 412th TW Rating Criteria below.

Circle a rating for each item or circle N/A for any item that does not apply. Please complete the following scale for items 1-11 and add any comments.

1. Rate the ease which with the AMPSS system was installed onto aircrew oxygen masks.

N/A 1 2 3 4 5 6

Comments: AMPSS 2.6 ISB (Inhale Sensor Block) contained all sensors within the inline assembly, which connects to the hose O2 connector and CRU-60/P connector. Very quick and easy, and a considerable improvement from AMPSS 1.0, 2.0 and 2.5. No ESB (Exhale Sensor Block) was available for the HAVE HOPE centrifuge or flight test to evaluate.

2. Rate the usefulness of instructions and manuals provided by the manufacturer for installation of the AMPSS

N/A 1 2 3 4 5 6

Comments: The AIMS (Aircrew Integrated Monitoring System) ISB operator user manual provided was very detailed and comprehensive. However, it didn't include the complete AMPSS 3.0 complete suite of components to include the Exhale Sensor Block. ESB Diagrams and actual ISB and ESB mounting instructions with pictures will be needed in future versions to complete the AMPSS 2.6 suite.

3. Rate the difficulty of pre-flight inspection/action requirements with AMPSS.

N/A 1 2 3 4 5 6

Comments: The ISB ppO2 sensors component require a preflight sensor calibration in a humidity level less than 3% to operate efficiently. This requires the complete ISB unit to be inserted in a humidity wicking substance prior to flight which is time consuming and requires materials not located in an AFE/Aircrew Life Support Shop.

4. Rate the difficulty of post-flight inspection/action requirements with AMPSS.

N/A 1 2 3 4 5 6

Comments: Post flights are easy with AMPSS 2.6 and is of no consequence.

5. Rate AMPSS reliability compared to the unmodified system.

N/A 1 2 3 4 5 6

Comments: Reliability comparison to unmodified system during centrifuge spins is all that was tested. No problems encountered, and data were collected. Actual flight reliability to unmodified still needs to be tested for evaluation.

6. Rate AMPSS maintainability compared to the unmodified system.

N/A 1 2 3 4 5 6

Comments: AMPSS 2.6 maintainability compared to the unmodified system seems easy and was only tested after the HAVE HOPE centrifuge spins.

7. Rate the difficulty of performing any required cleaning/ repair/maintenance actions.

N/A 1 2 3 4 5 6

Comments: AMPSS 2.6 required cleaning is limited to exterior of ISB component only. No physical repair or maintenance is allowed with the exception of software modifications. So, no difficulty noted.

8. Rate the adequacy of manufacturer's user/maintenance manual for any required inspection/repair/cleaning.

N/A 1 2 3 4 5 6

Comments: ISB Operator User Manual covers inspection and cleaning sufficiently. Cleaning is only allowed on exterior of complete unit. No physical component repairs are mention, short of replacing complete unit.

9. Rate the ease of removal of the AMPSS from oxygen hose.

N/A 1 2 3 4 5 6

Comments: Ease of removal from the ISB inline connect is very easy and is of no consequence. No ESB (Exhale Sensor Block) was available for the HAVE HOPE centrifuge or flight test to evaluate.

10. Overall, compare the AMPSS modified system to the baseline mask considering installation, pre/post flight actions, maintenance, and uninstallation.

N/A 1 2 3 4 5 6

Comments: Overall comparison of AMPSS 2.6 from baseline mask installation, pre/post flight actions, maintenance, and uninstallation function is relatively easy and satisfactory. However, no ESB (Exhale Sensor Block) was available for the HAVE HOPE centrifuge or flight test to evaluate, and this is necessary to compare the system suite overall.

11. Are special tools or equipment not normally available in your section required for any inspection/maintenance actions? NO, AMPSS 2.6 requires no special tools for inspection or maintenance actions.

If yes, list tools or equipment not available

Subject A

AMPSS 3.0 AIRCREW SURVEY

Use the 412th TW Rating Criteria below.

Circle a rating for each item or circle N/A for any item that does not apply. Please complete the following scale for items 1-20 and add any comments.

PRE-FLIGHT (Items 1-8)

1. Rate the ease with which you accomplished your AMPSS pre-flight compared to the baseline system.

N/A 1 2 3 4 5 6

Comments: I do not have experience with the baseline system, this system was easy to use.

2. Rate the pre-flight effort required to ensure proper AMPSS data collection.

N/A 1 2 3 4 5 6

3. Rate the ease of storage and transportation of the AMPSS system from AFE to the aircraft.

N/A 1 2 3 4 5 6

4. Rate the ease of ingress into the aircraft with the AMPSS system compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments: I do not have experience with the baseline system, but this system was easy to ingress to the aircraft.

5. Rate the ease of storage/arrangement of AMPSS components in the cockpit/on your person.

N/A 1 2 3 4 5 6

6. Rate the ease of connecting and turning on the AMPSS system in the cockpit

N/A 1 2 3 4 5 6

Comments: I never actually used the system in the cockpit, but in the centrifuge I never turned it on from the cockpit, it was already running.

7. Rate the overall comfort of the AMPSS system on the ground compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments: I do not have experience with the baseline system, but this system was minimally invasive and comfortable. If it could be integrated into a CRU style connector so that it would be even more compact, that would be even better!

8. Rate any control or visual interference caused by the AMPSS on the ground

N/A 1 2 3 4 5 6

AIRBORNE (Items 9-15)

9. Rate the overall comfort of the AMPSS system in the air compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments: I do not have experience with the baseline system, but this system was comfortable during use in the centrifuge.

10. Rate the overall comfort of the AMPSS system in the air while under high G-forces compared to baseline configuration.

N/A 1 2 3 4 5 6

Comments: I do not have experience with the baseline system, but this system was not noticeable during G-loading

11. Rate any control or visual interference caused by the AMPSS in the air.

N/A 1 2 3 4 5

12. Rate any control or visual interference caused by the AMPSS in the air while under high G-forces.

N/A 1 2 3 4 5 6

Comments: None

13. Rate any changes in breathing pressure or resistance caused by the AMPSS itself.

N/A 1 2 3 4 5 6

14. Rate the ease of storage/arrangement/security of AMPSS components in the cockpit/on your person while airborne.

N/A 1 2 3 4 5 6

Comments: Having it connected to the CRU-60 while going to and from the centrifuge felt odd, but did not hamper my ability to ingress or egress the cockpit. I would prefer an integrated unit, like a CRU-120 and AMPSS in one. That would be the ultimate equipment piece right there.

15. Rate the ease of storage/arrangement/security of AMPSS components in the cockpit/on your person while airborne under high G-forces.

N/A 1 2 3 4 5 6

Comments: None noticed.

POST-FLIGHT (Items 16-18)

16. Rate the ease of normal egress out of the aircraft with the AMPSS system compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments: No problems noticed

17. Rate the ease of emergency egress out of the aircraft with the AMPSS system compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments: I do not have experience with the baseline system, but this system was easy to get out of the centrifuge with.

18. Rate the ease with which you accomplished your AMPSS post-flight compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments: do not have experience with baseline system, this system was easy to postflight.

GENERAL RATINGS (Items 19-20)

19. Rate the ease with which the AMPSS system could be widely implemented from an aircrew perspective.

N/A 1 2 3 4 5 6

Comments: With minimal training, this system could be easily integrated.

20. Rate the overall comfort of the AMPSS modified mask compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments: I did not get any experience with the mask.

Subject B

AMPSS 3.0 AIRCREW SURVEY

Use the 412th TW Rating Criteria below.

Circle a rating for each item or circle N/A for any item that does not apply. Please complete the following scale for items 1-20 and add any comments.

PRE-FLIGHT (Items 1-8)

1. Rate the ease with which you accomplished your AMPSS pre-flight compared to the baseline system.

N/A 1 2 3 4 5 6

Comments:

2. Rate the pre-flight effort required to ensure proper AMPSS data collection.

N/A 1 2 3 4 5 6

Comments:

3. Rate the ease of storage and transportation of the AMPSS system from AFE to the aircraft.

N/A 1 2 3 4 5 6

Comments:

4. Rate the ease of ingress into the aircraft with the AMPSS system compared to the baseline compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments:

5. Rate the ease of storage/arrangement of AMPSS components in the cockpit/on your person.

N/A 1 2 3 4 5 6

Comments:

6. Rate the ease of connecting and turning on the AMPSS system in the cockpit

N/A 1 2 3 4 5 6

Comments:

7. Rate the overall comfort of the AMPSS system on the ground compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments:

8. Rate any control or visual interference caused by the AMPSS on the ground

N/A 1 2 3 4 5 6

AIRBORNE (Items 9-15)

9. Rate the overall comfort of the AMPSS system in the air compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments:

10. Rate the overall comfort of the AMPSS system in the air while under high G-forces compared to baseline configuration.

N/A 1 2 3 4 5 6

Comments:

11. Rate any control or visual interference caused by the AMPSS in the air.

N/A 1 2 3 4 5 6

Comments:

12. Rate any control or visual interference caused by the AMPSS in the air while under high G-forces.

N/A 1 2 3 4 5 6

Comments:

13. Rate any changes in breathing pressure or resistance caused by the AMPSS itself.

N/A 1 2 3 4 5 6

Comments:

14. Rate the ease of storage/arrangement/security of AMPSS components in the cockpit/on your person while airborne.

N/A 1 2 3 4 5 6

Comments:

15. Rate the ease of storage/arrangement/security of AMPSS components in the cockpit/on your person while airborne under high G-forces.

N/A 1 2 3 4 5 6

Comments:

POST-FLIGHT (Items 16-18)

16. Rate the ease of normal egress out of the aircraft with the AMPSS system compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments:

17. Rate the ease of emergency egress out of the aircraft with the AMPSS system compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments:

18. Rate the ease with which you accomplished your AMPSS post-flight compared to the baseline configuration.

N/A 1 2 3 4 5 6

GENERAL RATINGS (Items 19-20)

19. Rate the ease with which the AMPSS system could be widely implemented from an aircrew perspective.

N/A 1 2 3 4 5 6

20. Rate the overall comfort of the AMPSS, compared to the baseline configuration.

N/A 1 2 3 4 5 6

Comments:

Appendix L – Phase 1 Subjects 1-7 Elbit vs. Wyle HR Sensor

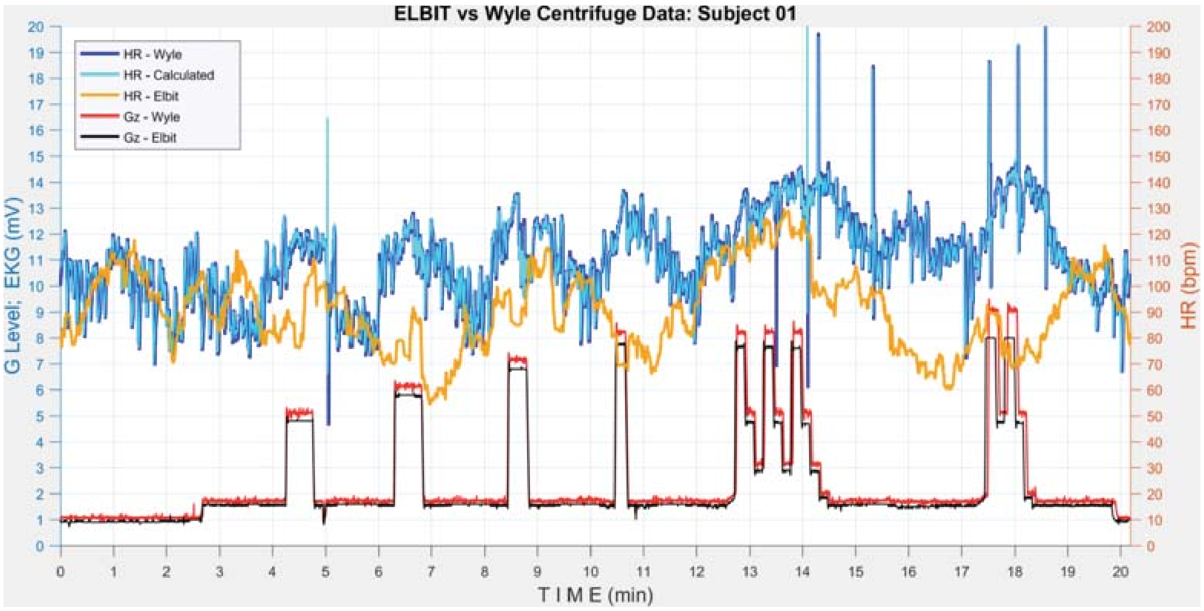


Figure 108: Phase 1 Subject 1 Elbit vs. Wyle HR Data

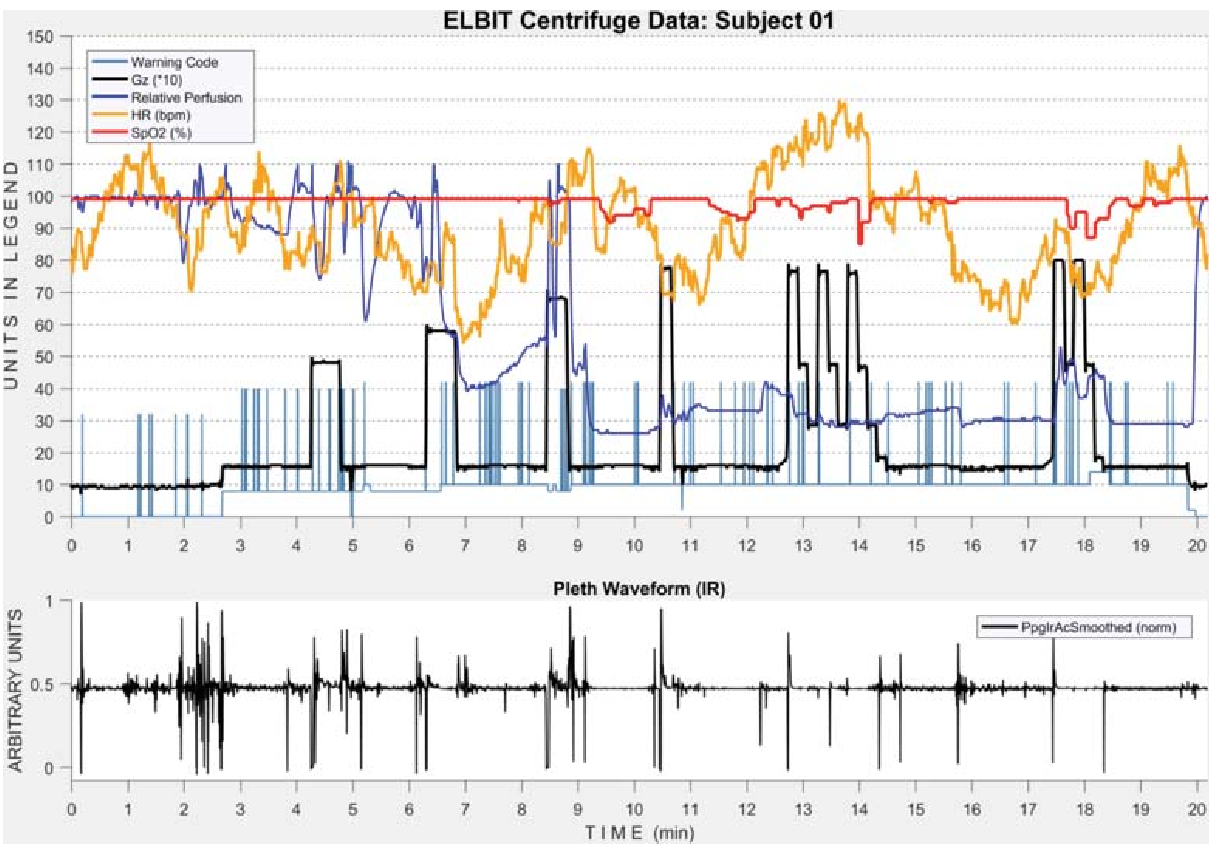


Figure 109: Phase 1 Subject 1 Elbit Data

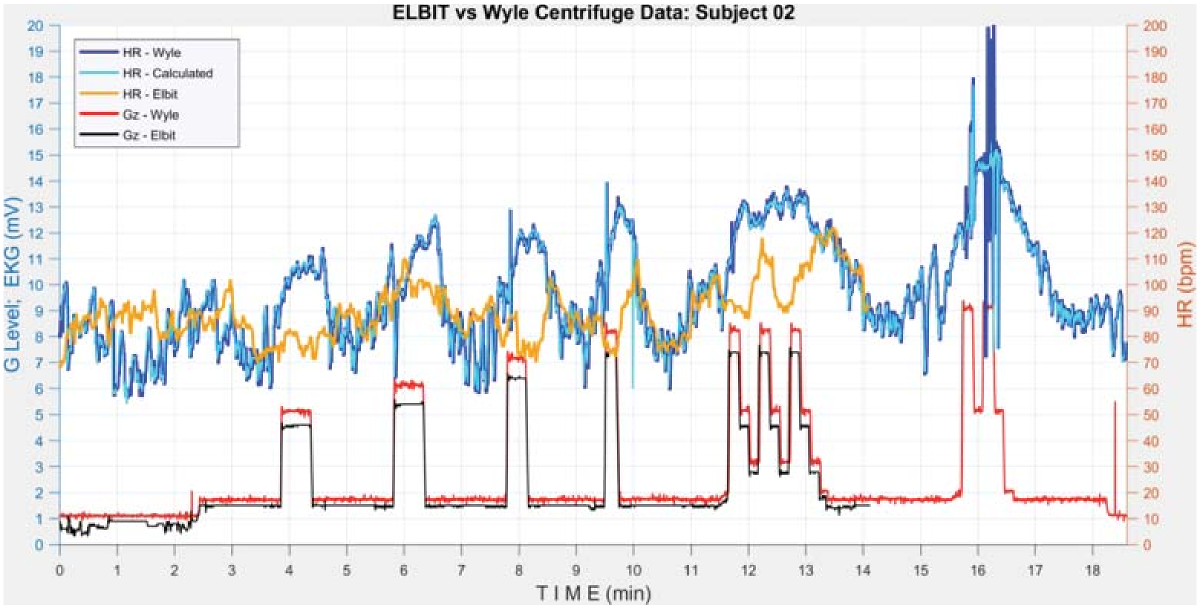


Figure 110: Phase 1 Subject 2 Elbit vs. Wyle HR Data

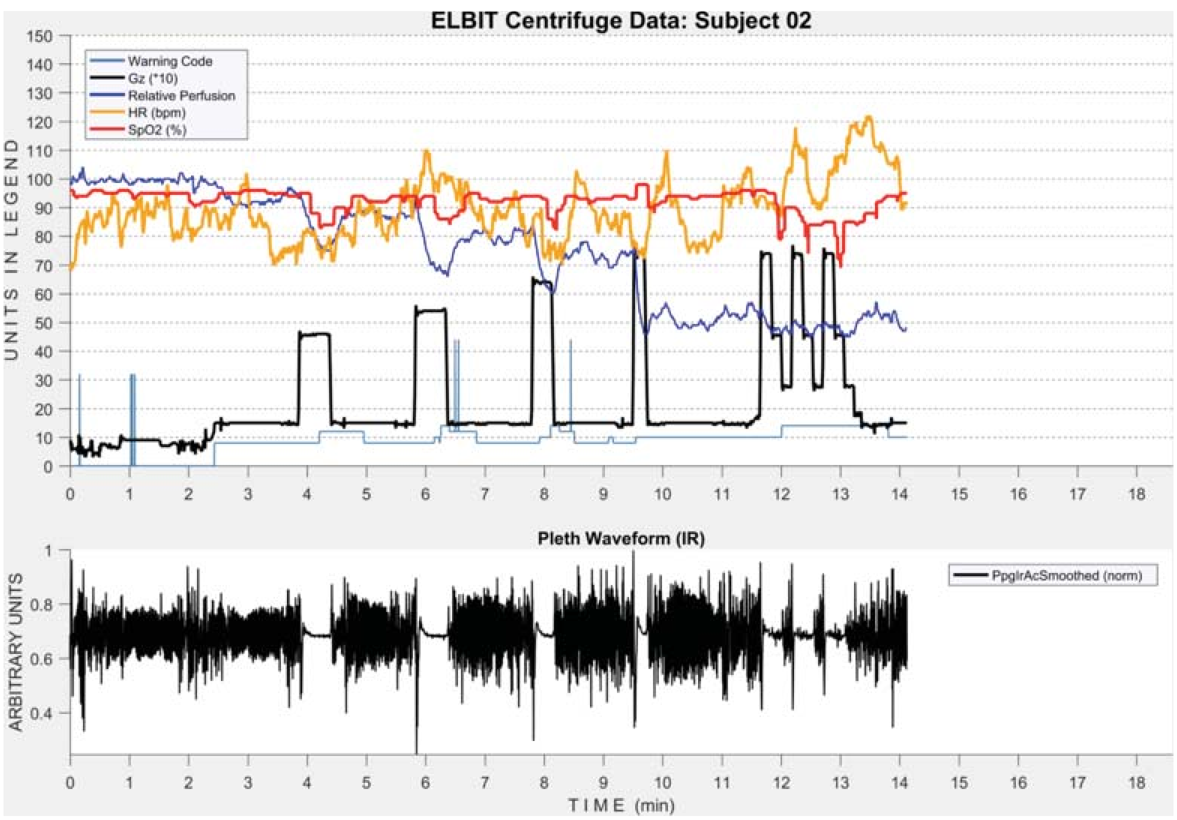


Figure 111: Phase 1 Subject 1 Elbit Data

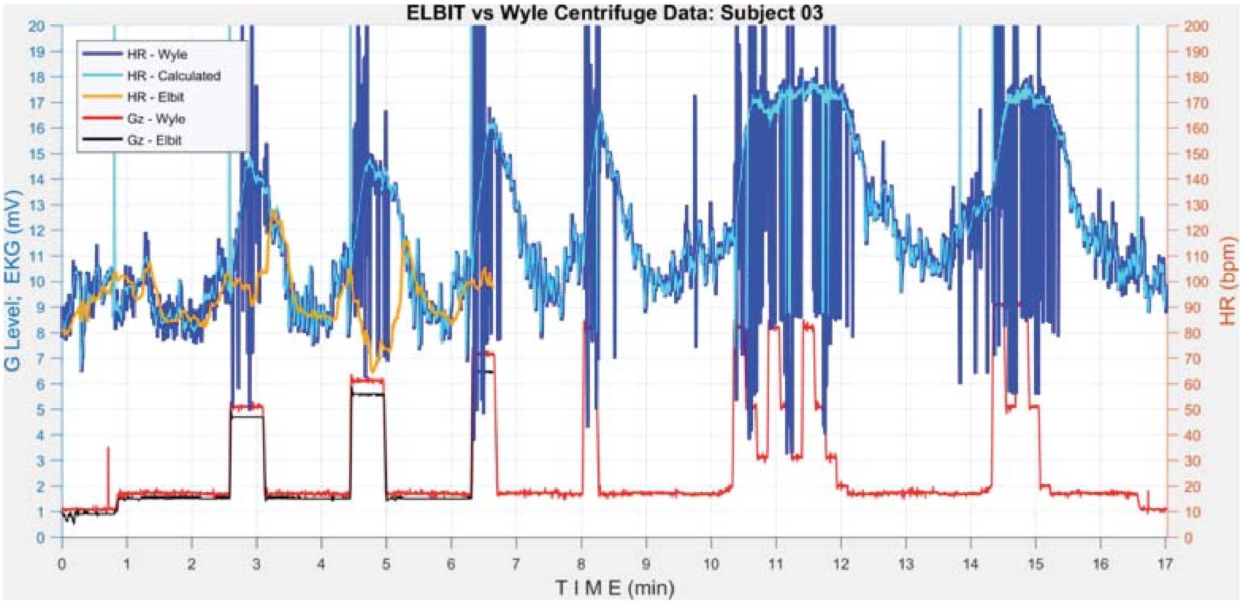


Figure 112: Phase 1 Subject 3 Elbit vs. Wyle HR Data

****Other Elbit Data Unavailable****

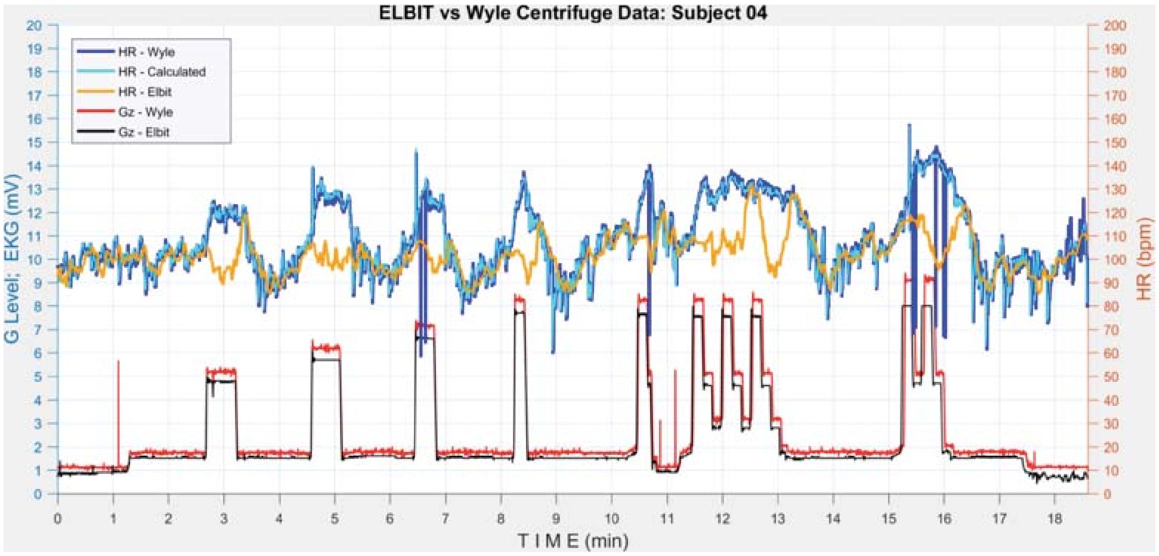


Figure 113: Phase 1 Subject 4 Elbit vs. Wyle HR Data

**Good Example: ELBIT HR inaccurate under G; Matches Wyle truth data at resting G.

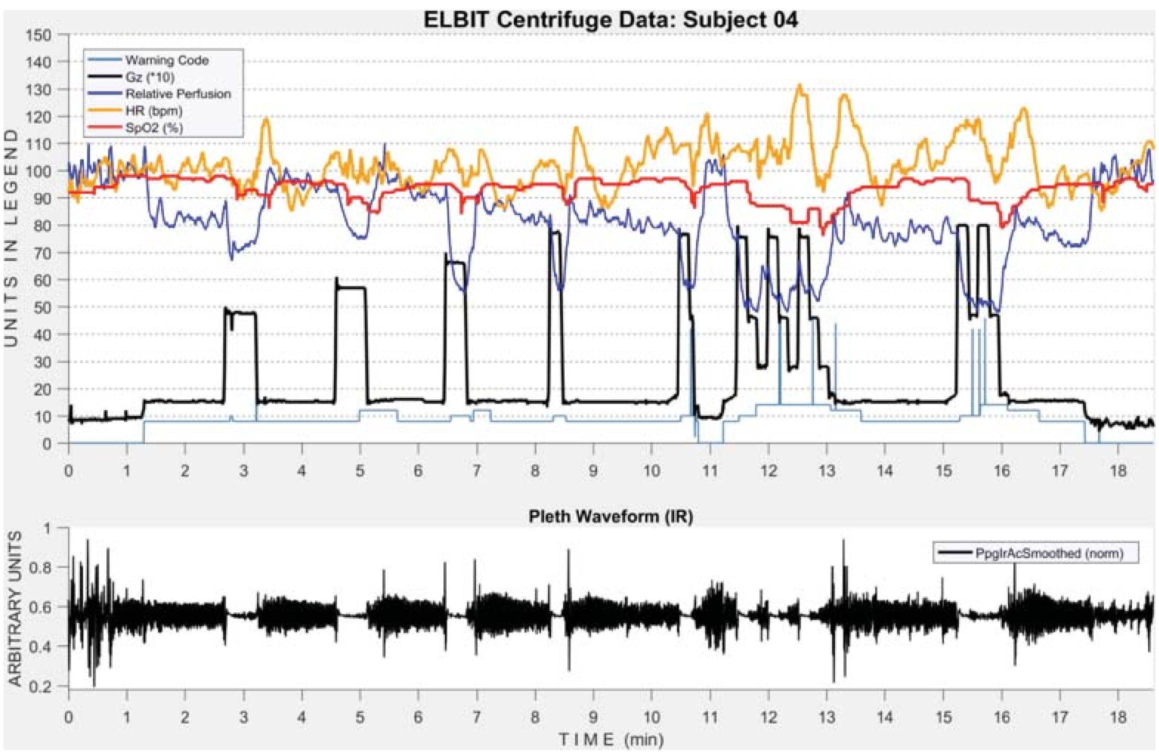


Figure 114: Phase 1 Subject 4 Elbit Data

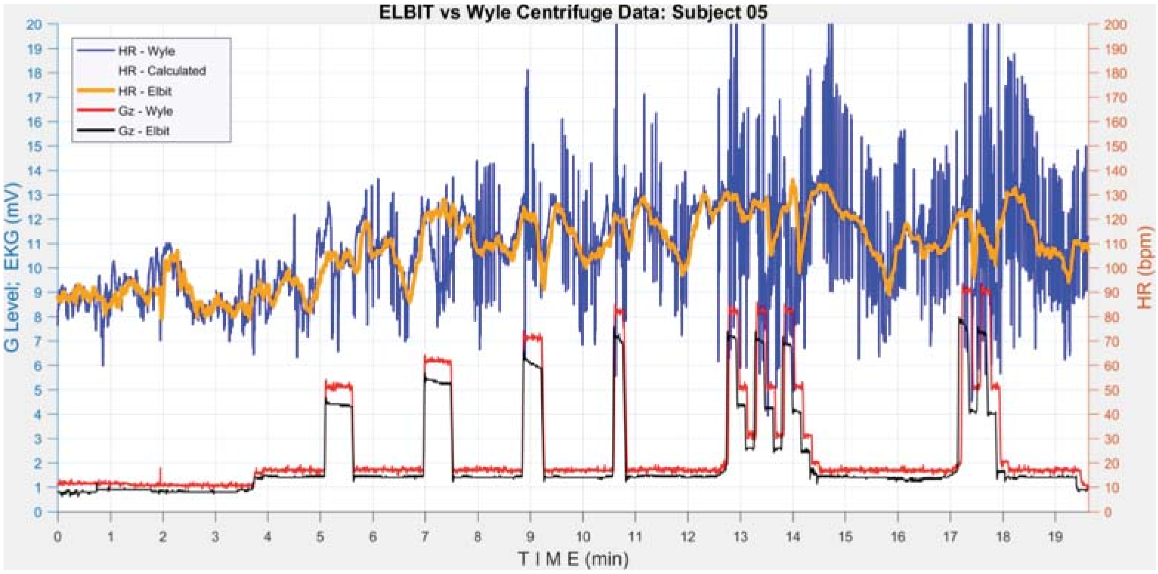


Figure 115: Phase 1 Subject 5 Elbit vs. Wyle HR Data

- Very noisy Wyle ECG signal, hence calculated HR is not shown.
- Elbit Pleth signal is good. ELBIT traces (hypothetical) smoothed version of Wyle HR.
- Only phase 1 instance in which Elbit is accurate and Wyle HR is not accurate.

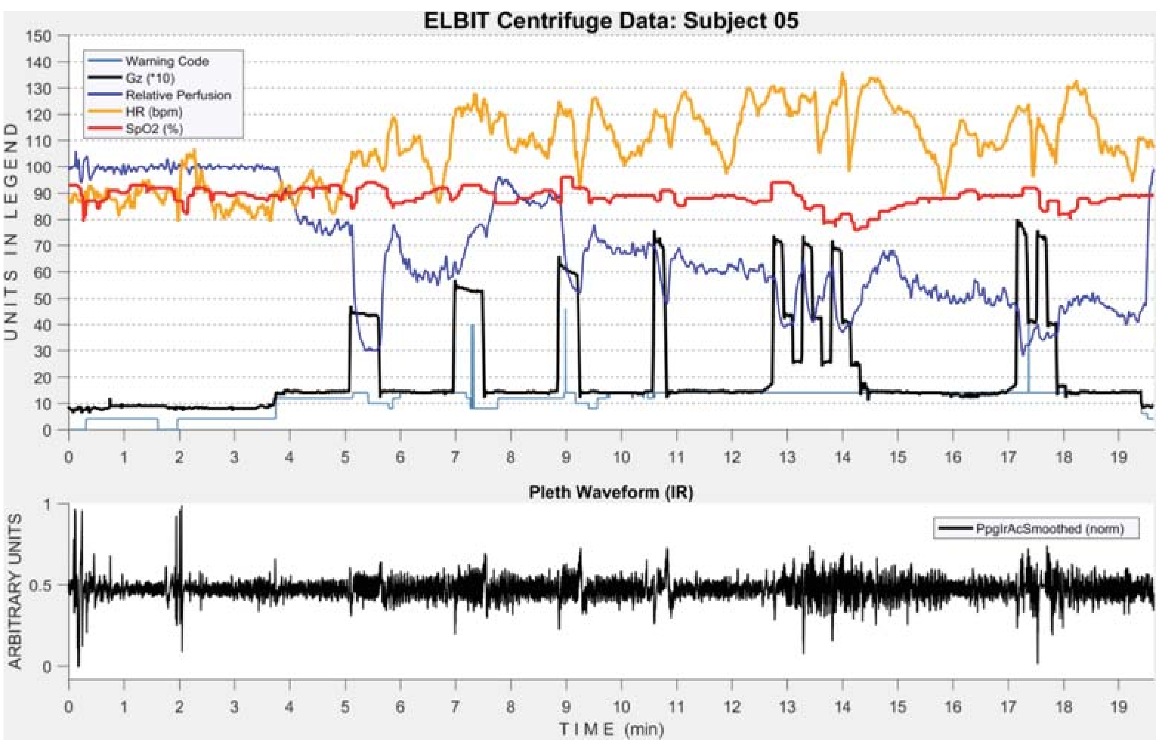


Figure 116: Phase 1 Subject 5 Elbit Data

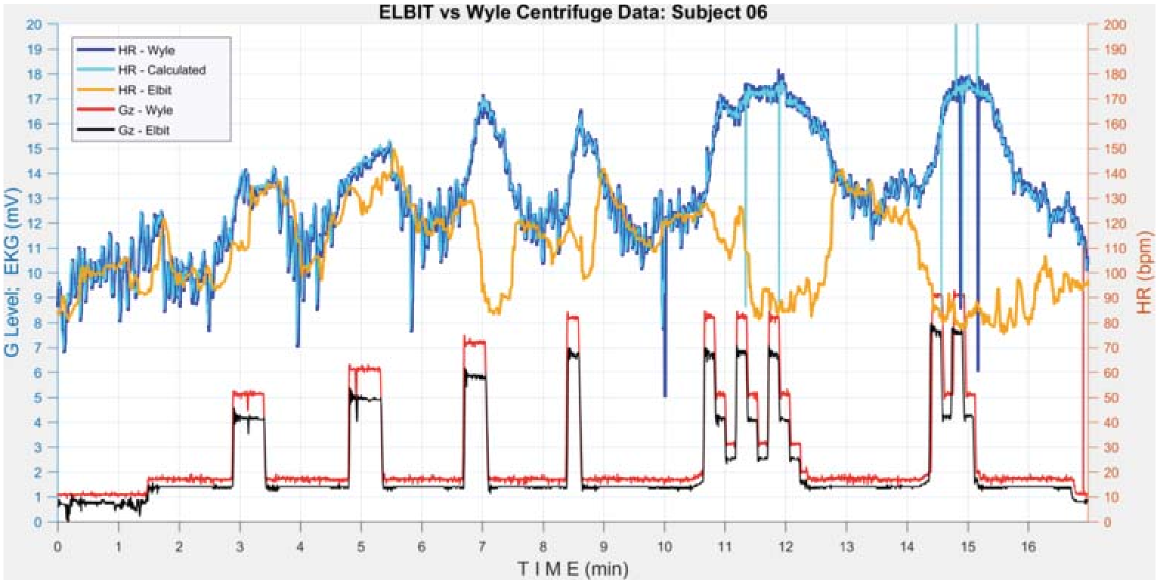


Figure 117: Phase 1 Subject 6 Elbit vs. Wyle HR Data

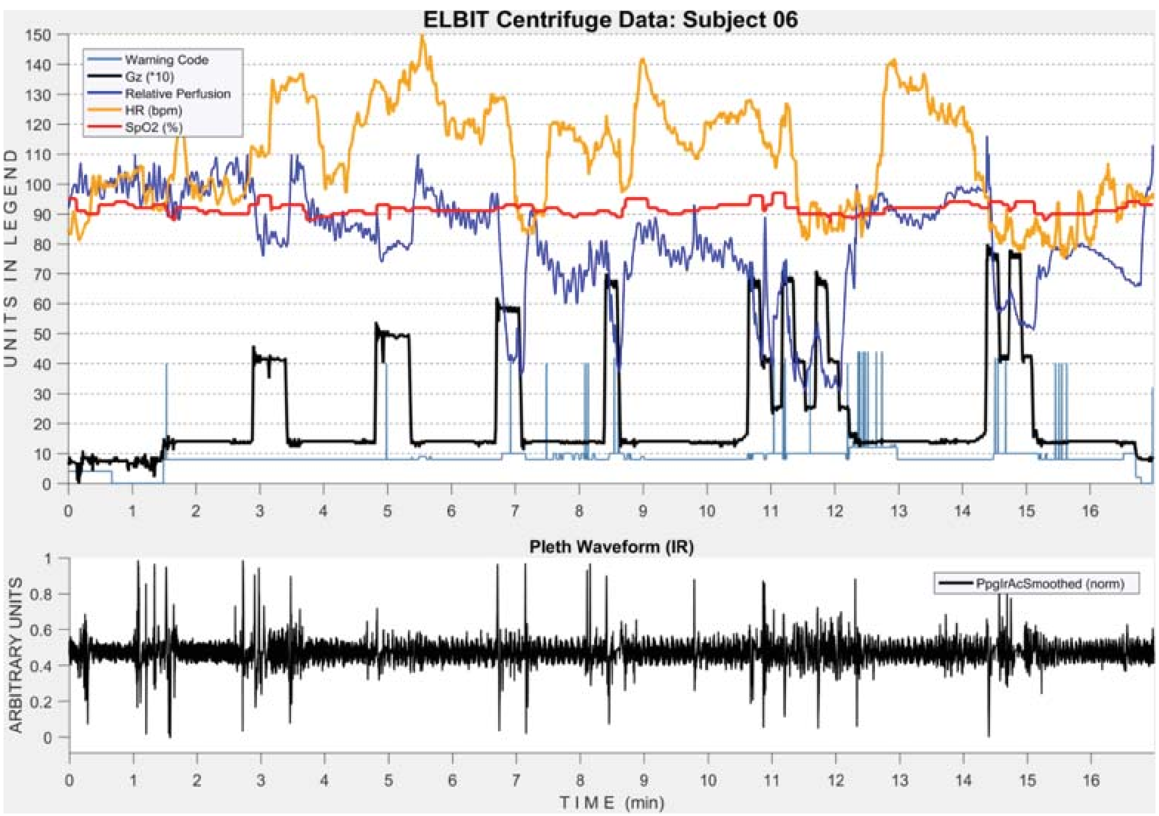


Figure 118: Phase 1 Subject 6 Elbit Data

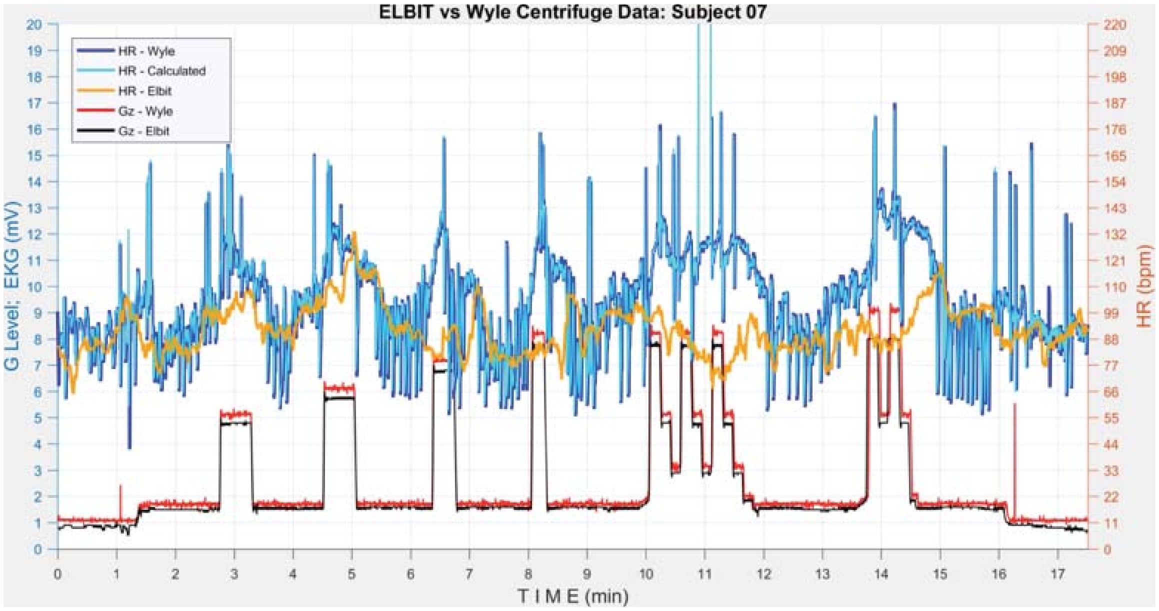


Figure 119: Phase 1 Subject 7 Elbit vs. Wyle HR Data

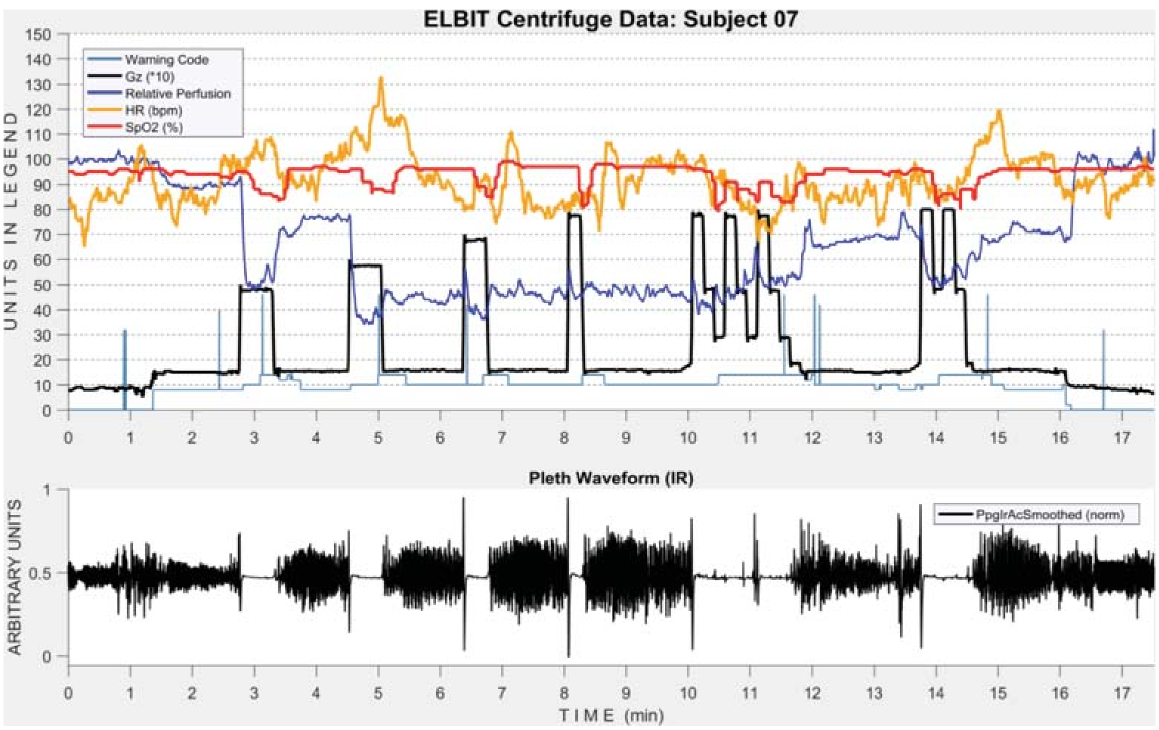


Figure 120: Phase 1 Subject 7 Elbit Data

Appendix M – Statistical Analysis

Statistical Analysis
Preliminary Report of Results (PR^2)
TPS Class 17A HAVE HOPE Test Project

Prepared by Rita Caraig M.S.
812 TSS/ENTR
09-Oct 2017 (Version not reviewed)

Data Description

A total of 140 independent data points were submitted for statistical analysis by Capt. Weston Hanoka and Capt. Mark Shaker, USAF TPS to Statistics Flight. All data points were collected and summarized from individual data cards completed by the participating test pilots/evaluators/subjects.

Table 1: Table of Variables

Response Variables:	Factors Variables:
- HR from Wyle, Watch, PECGU - %HRR from Wyle, Watch, PECGU - Borg Score (Ordinal data) - Code %Accurate, Time (s) - Ops Time (s) - Stroop Color %Accurate, Time (s) - Stroop Word %Accurate, Time (s) - Time to complete Cog tasks (s) - Rest Time (s) - Test score - Tracking task accuracy (not available) - G-tracking task accuracy (not available)	-Centrifuge and In-flight (Categorical) -Aware and Unaware of PC State (Categorical) -Evaluators (Test Pilot) -Date or Runs

Measures of Performance: Borg Score versus % HRR

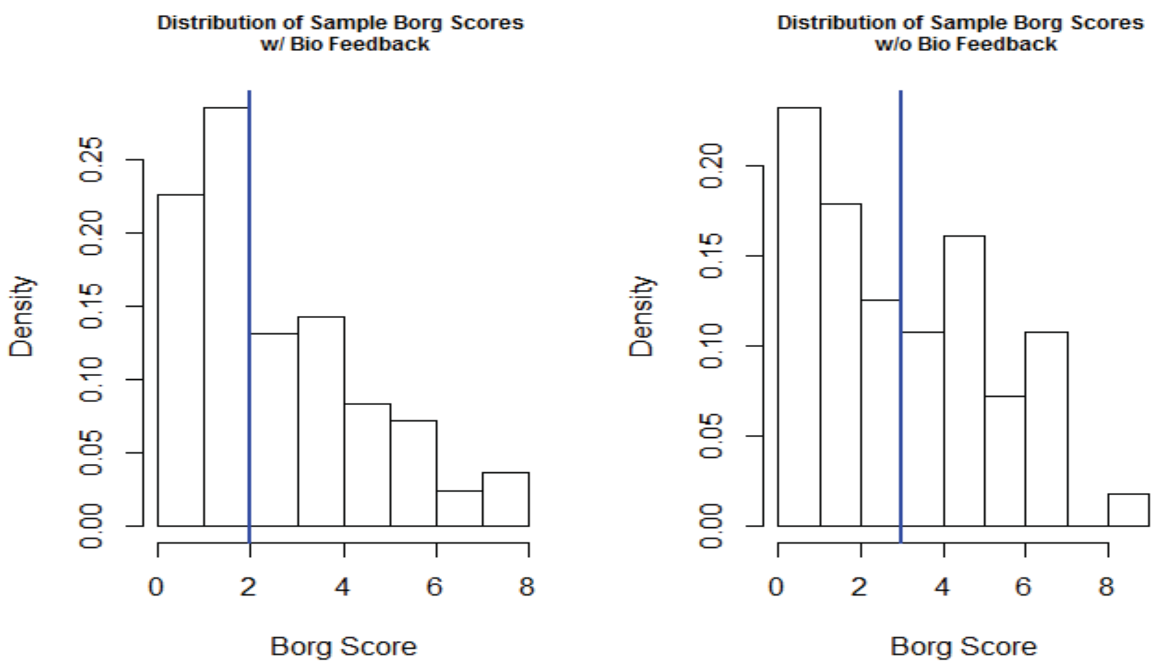
The summary statistics describe the average percent heart rate reserve (%HRR) by source of measurement (Wyle, Watch, PECGU) and by biofeedback awareness correlated with the Borg scores.

Borg Score	Average of %HRR Wyle		Average of %HRR Watch		Average of %HRR PECGU	
	No	Yes	No	Yes	No	Yes
0	0.28	0.27		0.29		0.26
1	0.39	0.34	0.40	0.40		0.43
2	0.52	0.50	0.50	0.44		0.50
3			0.56	0.55		0.63
4	0.60	0.56	0.77	0.48		0.63
5	0.58	0.62	0.71	0.53		0.52
6	0.71	0.66	0.67	0.42		0.60
7	0.72	0.70		0.32		0.83
8		0.83				
9	0.75					
Overall	**0.56**	**0.55**	**0.56**	**0.45**		**0.53**
Correlation, r	**0.95**	**0.98**	**0.84**	**0.15**		**0.85**

High correlation coefficients (0.95, 0.98) between Borg score and average %HRR derived from Wyle both aware and unaware PC state suggest a very strong linear relationship. Correlation is the weakest between Borg score and average %HRR derived from watch and at aware state (r=0.15).

Measures of Performance: Borg Score versus PC Awareness

In comparing Borg scores between biofeedback awareness states (Yes/No), the two histograms show the median Borg score without biofeedback is slightly higher than that of with biofeedback. Non-parametric median test between two samples proves that this difference is not statistically significant (Kruskal Wallis Chi-square p-value =0.2522). A parametric t-test result also proves a non-significant average difference between with and without biofeedback (Welch T p-value=0.2137)

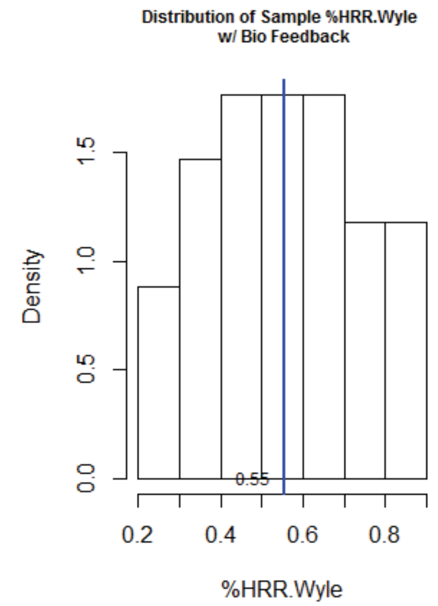


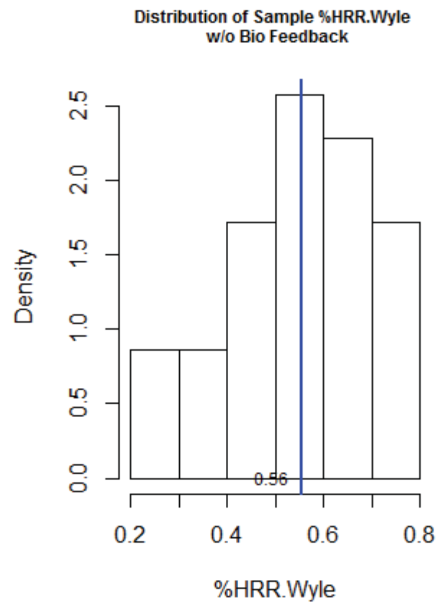
Measure of Performance: Percent HRR versus Biofeedback Awareness

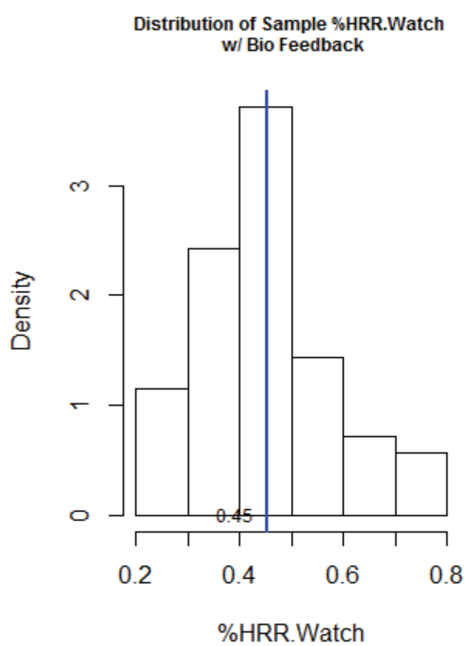
Average percent heart rate is summarized in the table below by method (centrifuge and flight) and by source of measurements (Wyle, Watch and PECGU). Empty cells implies no inferential comparison of average or median can be made due to lack of data.

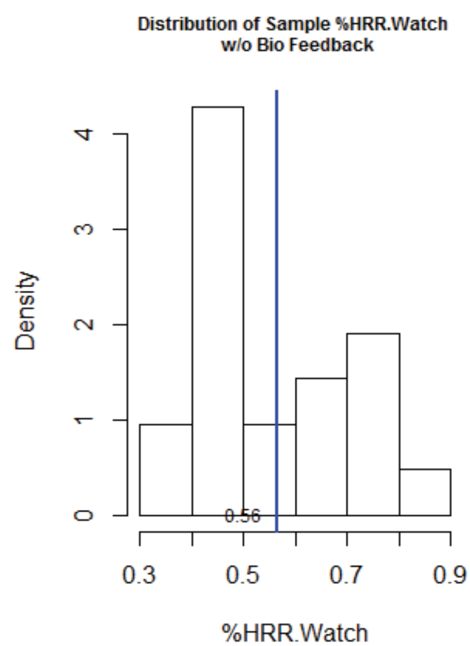
Method	Average of %HRR Wyle		Average of %HRR Watch		Average of %HRR PECGU	
	No	Yes	No	Yes	No	Yes
Centrifuge	0.56	0.55		0.40		0.48
Flight			0.56	0.48		0.54

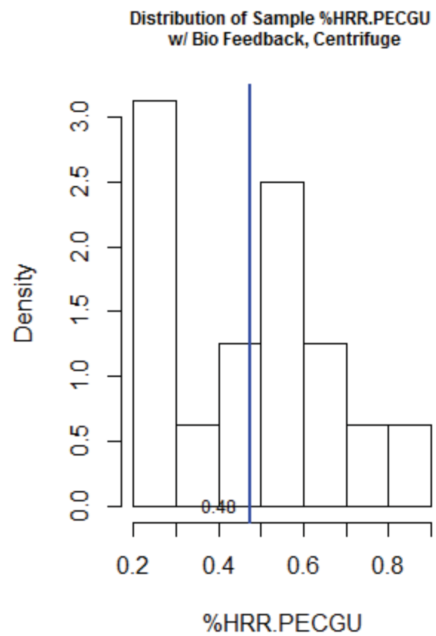
The distribution of sample % HRR and average between with and without biofeedback is also shown in the pairwise histogram below.

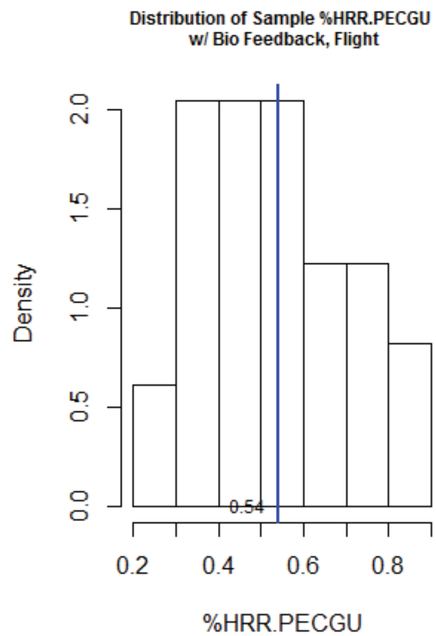












Classic ANOVA Hypothesis Test
Null: Factor does not affect the variability of %HRR or means are equal
Alt: Factor affects the variability of %HRR or means are different
Rejection Rule: Reject Null if P-value < 5%

ANOVA OUTPUT

```
Response: X.HRR.Wyle
                           Df  Sum Sq  Mean Sq F value Pr(>F)
BioFeedback                 1 0.00006 0.000061  0.0023 0.9619
Test.Subject                4 0.18469 0.046172  1.7412 0.1530
BioFeedback:Test.Subject    4 0.05348 0.013371  0.5042 0.7327
Residuals                  59 1.56449 0.026517
```

No strong evidence to suggest that the average %HRR Wyle between aware and non-aware state at centrifuge is different.

```
Response: X.HRR.Watch
                 Df  Sum Sq  Mean Sq F value    Pr(>F)
BioFeedback       1 0.19648 0.196478 12.7113 0.0005964 ***
Centrifuge.Flight 1 0.09376 0.093760  6.0659 0.0157756 *
Test.Subject      2 0.18493 0.092465  5.9820 0.0036945 **
Residuals        86 1.32930 0.015457
```

***strong evidence that the average %HRR Watch is different between aware and non-aware state, between methods (centrifuge and flight), and evaluators.

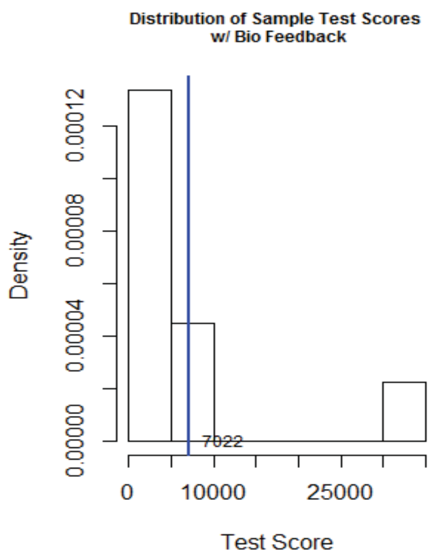
```
Response: X.HRR.PECGU
                                Df  Sum Sq  Mean Sq F value    Pr(>F)
Centrifuge.Flight                1 0.05353 0.053532  2.4634    0.1219
Test.Subject                     3 0.79605 0.265349 12.2110 2.557e-06 ***
Centrifuge.Flight:Test.Subject   1 0.01411 0.014109  0.6493    0.4236
Residuals                       59 1.28209 0.021730
```

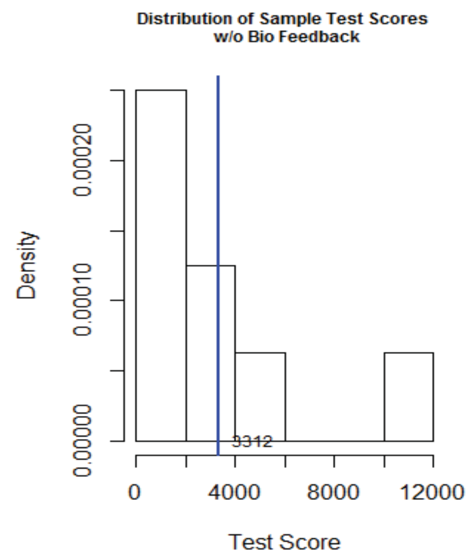
Difference in average %HRR PECGU is due primarily to subject or evaluator variability.

Measure of Performance: Test Score

The table below shows the average test scores by method, by biofeedback awareness, and by subject or test pilot.

Test Subject (Test Score)	Centrifuge			Flight		
	No	Yes	Combined	No	Yes	Combined
A	5438		5438	603	1137	870
B	1384	9451	5417	2124	2411	2315
C	1866	1979	1922	528	1211	983
D	2882	8999	5941			
E	11675	34394	23034			
Overall	**4649**	**13706**	**8674**	**1085**	**1676**	**1454**





ANOVA OUTPUT

```
Response: d$Test.Score..lower.is.better
                  Df    Sum Sq   Mean Sq F value   Pr(>F)
BioFeedback        1  58298220  58298220  2.6029 0.137742
Centrifuge.Flight  1 272513137 272513137 12.1672 0.005841 **
Test.Subject       4 530109060 132527265  5.9171 0.010436 *
Residuals         10 223972789  22397279
```

Difference in average test scores is due primarily to methods (centrifuge vs. flight) and test subjects. Awareness of biofeedback has shown no significant effect on the average test scores.

Appendix N – Daily Flight Reports

DAILY/INITIAL FLIGHT TEST REPORT	1. AIRCRAFT TYPE	2. SERIAL NUMBER
	F-16DM	90-0797

3. CONDITIONS RELATIVE TO TEST

A. PROJECT / MISSION NO	B. FLIGHT NO / DATA POINT	C. DATE
HAVE HOPE / 1	C1 / No Biofeedback	5 Sep 2017
D. FRONT COCKPIT (Left Seat)	**E. FUEL LOAD**	**F. JON**
Subject C	7,960 lbs	MT17A200
G. REAR COCKPIT (Right Seat and rest of crew)	**H. START UP GR WT / CG**	**I. WEATHER**
Test Conductor	29,509 lbs / 39.09%	SKC
J. TO TIME / SORTIE TIME	**K. CONFIGURATION / LOADING**	**L. SURFACE CONDITIONS**
1246L / 0.6	CL Tank	VRB06, Dry, 37°C
M. CHASE ACFT / SERIAL NO	**N. CHASE CREW**	**O. CHASE TO TIME / SORTIE TIME**
N/A	N/A	N/A

4. PURPOSE OF FLIGHT / TEST POINTS

To collect physiological and cognitive state data with biofeedback available to the test pilot under high G environment IAW HAVE HOPE Test Plan procedures.

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Mission Profile:
Ground Block / Taxi/ Takeoff / GX
Test Set 1 (6, 5, 3, 8, 5, 3, 8, 5, 3) (Each G point held for 10 seconds, 2 second transitions between points)
Rest/Cognitive Test: Borg, Light Loss, Code Recall, Ops Check, Stroop (words and colors) – call when ready next, read next code
Test Sets 2-4: repeat above

Biofeedback display failed in EOR. Tried to troubleshoot, but flexed to no-biofeedback profile.

Test Set 1:
Data collection satisfactory. Energy management not ideal. TP lost energy during 6G in MIL power and busted 15 deg NL restriction. Per brief, test set should have been terminated. Slow to regain energy for follow-on 8G points. PC state data under amplifying comments.

Test Set 2:
Profile flown satisfactorily. Data collection satisfactory.

Test Set 3:
Profile flown satisfactorily. Data collection satisfactory.

Test Set 4:
Profile limited due to beginning profile at 2,000 lbs and limited to no AB use. 8G points flown in MIL power. Unable to fly last 3G point, used time to accelerate for last 8G pull.

Amplifying Comments:
Below is a list of physiological and cogitative state experiences noted by the pilot during execution of the profile.

- TP noted lacking ability to re-call random codes compared to centrifigue. Mental workload to fly profile much higher than mental workload to AGSM only in centrifuge where code recall was much easier.
- Pilot noted fairly low mental workload. Ready in min rest time.

6. RECOMMENDATIONS

R1: Start altitude at 14k' unnecessary. Starting at lower altitude and .95M, can keep enery on jet longer and avoid getting slow
R2: In brief, address exceedance of 15 deg NL as an advisory call from control room, not an immediate terminate of test set. If no positive correction made, issue second advisory call and terminate after 1 second if no correction.
R3: MIL power takeoffs from now on. Max AB lead to fuel limited by end to get 4 test sets in.
R4: Fly next sortie with biofeedback.

COMPLETED BY	SIGNATURE	DATE
-----	Completed by Subject C	5 Sep 2017

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DAILY/INITIAL FLIGHT TEST REPORT	1. AIRCRAFT TYPE F-16DM	2. SERIAL NUMBER 90-00797

3. CONDITIONS RELATIVE TO TEST		
A. PROJECT / MISSION NO HAVE HOPE / 2	B. FLIGHT NO / DATA POINT 1 / With Biofeedback	C. DATE 5-Sep-17
D. FRONT COCKPIT *(Left Seat)* Subject A	E. FUEL LOAD 7800	F. JON MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)* Test Conductor	H. START UP GR WT / CG 28.9K / 35.2	I. WEATHER SCT 170
J. TO TIME / SORTIE TIME 0014Z 06 Sep / 0.5	K. CONFIGURATION / LOADING CAT I / 9000T000A	L. SURFACE CONDITIONS WIND 200/010
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A

4. PURPOSE OF FLIGHT / TEST POINTS

Test Objective: Gather Data IAW HAVE HOPE Test and Safety Plan

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Mission Profile:
1. Engine Start
2. Ground Block / Taxi
3. T/O -> G Ex
4. Test Set 1 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
5. Test Set 2 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
6. Test Set 3 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
7. Test Set 4 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
8. RTB

Prior to Engine start, TP noted a weekly rest score of 7 and a 24 hour rest score of 5 as well as a weekly hydration score of 7 and a 24 hour hydration score of 5. It was also noted that brief was a 0700L with no rest between brief and 1714L takeoff.

1. Engine Start - Uneventful. Minor comm issues contacting control room, carry over from first sortie of the day.

2. Ground Block / Taxi - Successful TM checks and administration of cognitive tests. BORG rating was 1, HR was 116, %HRR was 55, random code was 3/5 correct in 3.39 sec, and ops check was 4/6 correct with the others being out of order over 18.35 sec.

3. T/O -> G-Ex - STROOP code 16 was read all correct in 3.3 seconds. MIL power takeoff, left turnout to PIRA. Airspace assigned was PIRA, Mercury Spin and Four Corners FL200 and below. Successful TM check passing 8K' PA and no further issues through G-Ex. Both TP and IP felt good after pulling 6.2 G's during second half of G-Ex. 1st G warmup resulted in HR of 137, %HRR of 65, and BORG of 2. After the second pull, HR was 138, %HRR was 57, and BORG of 2. 500 pounds of fuel were still in external centerline tank, so TP had to burn down until empty which took approximately 5-6 additional minutes.

6. RECOMMENDATIONS

REFLY BIO-FEEDBACK SORTIE FOR DATA

COMPLETED BY		DATE
Subject A	Completed by Subject A	06-Sep-17

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DAILY/INITIAL FLIGHT TEST REPORT

1. AIRCRAFT TYPE	2. SERIAL NUMBER
F-16DM	90-00797

3. CONDITIONS RELATIVE TO TEST

A. PROJECT / MISSION NO	B. FLIGHT NO / DATA POINT	C. DATE
HAVE HOPE / 3	B1 / Biofeedback	6 Sep 2017
D. FRONT COCKPIT *(Left Seat)*	E. FUEL LOAD	F. JON
Subject B	7,960 lbs	MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)*	H. START UP GR WT / CG	I. WEATHER
Test Conductor	29,509 lbs / 39.01%	SKC
J. TO TIME / SORTIE TIME	K. CONFIGURATION / LOADING	L. SURFACE CONDITIONS
1448L / 0.6	CL Tank	VRB06, Dry, 20.00, 39°C
M. CHASE ACFT / SERIAL NO	N. CHASE CREW	O. CHASE TO TIME / SORTIE TIME
N/A	N/A	N/A

4. PURPOSE OF FLIGHT / TEST POINTS

To collect physiological and cognitive state data with biofeedback available to the test pilot under high G environment IAW HAVE HOPE Test Plan procedures.

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Test Profile 1:
Profile discontinued during second 8G test point due to loss of energy. Due to the first profile for the flight and some unfamiliarity of the task and aircraft, the pilot allowed the energy to reduce to a point of no return and did not have the airspeed to achieve 8G during the second test point. A reason for this was not using afterburner long enough in the lead-up 3G point to allow the aircraft to accelerate. This technique was corrected for further test points.

Test Profile 2:
Profile discontinued during second 8G test point due to lower altitude limit termination call at 8000 feet MSL. Of note, an altitude bust did not occur as actual limit was 7300 feet MSL. The test pilot elected to apply a personal buffer as an advisement of an approaching hard limit (7300 feet). This technique was not properly conveyed to the IP and the IP called terminate at 8000 feet. Recommend setting 7300 feet as standard for further flights.

Test Profile 3:
Profile discontinued during third 5G test point due to FLCS malfunction. Data Physiological-Cognitive data collection immediately after termination then FLCS was reset.

Test Profile 4:
Profile discontinued during second 8G test point due to FLCS malfunction. Data Physiological-Cognitive data collection immediately after termination then FLCS was reset.

Amplifying Comments:

- The pilot considered this flight high workload due to a combination of learning the task and dealing with FLCS malfunction issues. The pilot stated assessment of biofeedback was not considered during any of the test sets because of other tasks being deemed more important. These tasks included airspace management, energy management and emergency procedure management.

6. RECOMMENDATIONS

None

COMPLETED BY	SIGNATURE	DATE
Subject B	Completed by Subject B	6 Sep 2017

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DAILY/INITIAL FLIGHT TEST REPORT

1. AIRCRAFT TYPE	2. SERIAL NUMBER
F-16DM	87-00391

3. CONDITIONS RELATIVE TO TEST

A. PROJECT / MISSION NO	B. FLIGHT NO / DATA POINT	C. DATE
HAVE HOPE / 4	A2 / No Biofeedback	8-Sep-17
D. FRONT COCKPIT *(Left Seat)*	E. FUEL LOAD	F. JON
Subject A	7800	MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)*	H. START UP GR WT / CG	I. WEATHER
Test Conductor	28.9K / 35.2	SCT 170
J. TO TIME / SORTIE TIME	K. CONFIGURATION / LOADING	L. SURFACE CONDITIONS
1603Z 08 Sep / 0.5	CAT I / 9000T000A	WIND 200/010
M. CHASE ACFT / SERIAL NO	N. CHASE CREW	O. CHASE TO TIME / SORTIE TIME
N/A	N/A	N/A

4. PURPOSE OF FLIGHT / TEST POINTS

Test Objective: Gather Data IAW HAVE HOPE Test and Safety Plan

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Mission Profile:
1. Engine Start
2. Ground Block / Taxi
3. T/O -> G Ex
4. Test Set 1 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
5. Test Set 2 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
6. Test Set 3 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
7. Test Set 4 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
8. RTB

Prior to Engine start, TP noted a weekly rest score of 7 and a 24 hour rest score of 6 as well as a weekly hydration score of 7 and a 24 hour hydration score of 6.

1. Engine Start - Uneventful. Minor comm issues contacting control room.

2. Ground Block / Taxi - Successful TM checks and administration of cognitive tests. BORG rating was 1, random code was X/5 correct in XX sec, and ops check was X/6 correct with the others being out of order over XX:XX sec.

3. T/O -> G-Ex - STROOP code XX was read all correct in X seconds. MIL power takeoff, left turnout to PIRA. Airspace assigned was PIRA, Mercury Spin and Four Corners 15,000 MSL and below. Successful TM check passing 8K' PA and no further issues through G-Ex. Both TP and TC felt good after pulling 6.4 G's during second half of G-Ex. 300 pounds of fuel were still in external centerline tank, so TP had to burn down until empty which took approximately 2-3 additional minutes.

6. RECOMMENDATIONS

None

COMPLETED BY	SIGNATURE	DATE
Subject A	Completed by Subject A	08-Sep-17

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DAILY/INITIAL FLIGHT TEST REPORT	1. AIRCRAFT TYPE F-16DM	2. SERIAL NUMBER 87-00391
3. CONDITIONS RELATIVE TO TEST		
A. PROJECT / MISSION NO HAVE HOPE / 5	B. FLIGHT NO / DATA POINT B2 / No Biofeedback	C. DATE 8 Sep 2017
D. FRONT COCKPIT (Left Seat) Subject B	E. FUEL LOAD 7,960 lbs	F. JON MT17A200
G. REAR COCKPIT (Right Seat and rest of crew) Test Conductor	H. START UP GR WT / CG 29,639 lbs / 39.77%	I. WEATHER SKC
J. TO TIME / SORTIE TIME 1511L / 0.7	K. CONFIGURATION / LOADING CL Tank	L. SURFACE CONDITIONS VRB06, Dry, 30.01, 39°C
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A

4. PURPOSE OF FLIGHT / TEST POINTS

To collect physiological and cognitive state data with biofeedback available to the test pilot under high G environment IAW HAVE HOPE Test Plan procedures.

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Test Set 1:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Test Set 2:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Test Set 3:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Test Set 4:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Amplifying Comments:
Below is a list of physiological and cogitative state experiences noted by the pilot during execution of the profile.

- The pilot noted a consistent increase in perceived physical exertion (borg scale) throughout the timeline of test profile. This was consistent with an increasing number of borg scale values given.
- Cognitive ability was assessed as greater than the previous flight. The pilot suggests this may be an influence of learning effect and an increased tolerance to the high g environment.

6. RECOMMENDATIONS

None

COMPLETED BY	SIGNATURE	DATE
Subject B	Completed by Subject B	8 Sep 2017

TPS Form 5314 NOV 86 NOT REALLY AN OFFICIAL FORM, BUT THIS IS WHAT WILL BE USED AT TPS

DAILY/INITIAL FLIGHT TEST REPORT	1. AIRCRAFT TYPE F-16D	2. SERIAL NUMBER 87-00391

3. CONDITIONS RELATIVE TO TEST

A. PROJECT / MISSION NO	B. FLIGHT NO / DATA POINT	C. DATE
HAVE HOPE / 7	B4 / Biofeedback	12 Sep 2017
D. FRONT COCKPIT *(Left Seat)*	E. FUEL LOAD	F. JON
Subject B	7,960 lbs	MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)*	H. START UP GR WT / CG	I. WEATHER
Test Conductor	29,639 lbs / 39.77%	FEW100
J. TO TIME / SORTIE TIME	K. CONFIGURATION / LOADING	L. SURFACE CONDITIONS
0753L / 0.6	CL Tank	VRB06, Dry, 29.98, 34°C
M. CHASE ACFT / SERIAL NO	N. CHASE CREW	O. CHASE TO TIME / SORTIE TIME
N/A	N/A	N/A

4. PURPOSE OF FLIGHT / TEST POINTS

To collect physiological and cognitive state data with biofeedback available to the test pilot under high G environment IAW HAVE HOPE Test Plan procedures.

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Test Set 1:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Test Set 2:
Profile flown satisfactorily. Just prior to the commencement of test set 2, the IP (Instructor Pilot) called terminate due to setup altitude requirements confusion. The flying pilot advised setup criteria was suitable and the test set was commenced. An approximate delay of 5 seconds resulted and should be added to the rest time between test set 1 and 2. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Test Set 3:
Profile flown satisfactorily. Data collection satisfactory. A radio call from SPORT occurred during the second 8G test point. The pilot elected to delay response and continue the test set. On completion of the test set, the pilot immediately responded to SPORT. This caused an approximate 3-5 second delay in assessing HR, HHR and Borg. This may induce error into the biofeedback data. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Test Set 4:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Amplifying Comments:
Below is a list of physiological and cogitative state experiences noted by the pilot during execution of the profile.

- Due to the early morning flight, the sun inhibited the pilots ability to read G on the HUD when passing through an easterly heading for approximately 2-3 second intervals. This may have impacted perceived tracking tolerances.
- The pilot noted a reduction in perceived physical exertion when compared to previous flights; however, the pilot felt his cogitative performance has reduced compared to previous flights.
- Finally, as per previous flights, the pilot deemed biofeedback readings as a lower priority when compared to other tasks. For example, the pilot would be more influenced to commence the next test set due to airspace or fuel limitations than due to what the biofeedback stated (Task focus weighed as a greater priority than biofeedback).

6. RECOMMENDATIONS

None

COMPLETED BY	SIGNATURE	DATE
Subject B	Completed by Subject B	12 Sep 2017

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Save

DAILY/INITIAL FLIGHT TEST REPORT	1. AIRCRAFT TYPE F-16DM	2. SERIAL NUMBER 87-00391
3. CONDITIONS RELATIVE TO TEST		
A. PROJECT / MISSION NO HAVE HOPE / 8	B. FLIGHT NO / DATA POINT A3 / with Biofeedback	C. DATE 12-Sep-17
D. FRONT COCKPIT *(Left Seat)* Subject A	E. FUEL LOAD 7800	F. JON MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)* Test Conductor	H. START UP GR WT / CG 28.9K / 35.2	I. WEATHER SCT 170
J. TO TIME / SORTIE TIME 1853Z 12 Sep / 0.5	K. CONFIGURATION / LOADING CAT I / 9000T000A	L. SURFACE CONDITIONS WIND 200/010
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A

4. PURPOSE OF FLIGHT / TEST POINTS

Test Objective: Gather Data IAW HAVE HOPE Test and Safety Plan

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Mission Profile:
1. Engine Start
2. Ground Block / Taxi
3. T/O -> G Ex
4. Test Set 1 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
5. Test Set 2 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
6. Test Set 3 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
7. Test Set 4 (6,5,3,8,5,3,8,5,3)
   REST: HRR, BORG, LL, CODE, OPS CHECK, STROOP
8. RTB

Prior to Engine start, TP noted a weekly rest score of 7 and a 24 hour rest score of 5 as well as a weekly hydration score of 7 and a 24 hour hydration score of 5.

1. Engine Start - Uneventful. Minor comm issues contacting control room.

2. Ground Block / Taxi - Successful TM checks and administration of cognitive tests. BORG rating was 1, random code was 5/5 correct in XX sec, and ops check was 6/6 correct over 7.4 sec.

3. T/O -> G-Ex - STROOP code 17 words and 8 colors were read all correct in X seconds. MIL power takeoff, left turnout to PIRA. Airspace assigned was PIRA, Mercury Spin and Four Corners 15,000 MSL and below. Successful TM check passing 8K' PA and no further issues through G-Ex. Both TP and TC felt good after pulling 6.4 G's during second half of G-Ex. 200 pounds of fuel were still in external centerline tank, so TP had to burn down until empty which took approximately 2 additional minutes. Borg was 1 during entire G-Ex and heart rate trended towards increasing during pulling G's, as reflected on data cards.

6. RECOMMENDATIONS

None

COMPLETED BY	SIGNATURE	DATE
Subject A	Completed by Subject A	12-Sep-17

TPS Form 5314 NOV 86 NOT REALLY AN OFFICIAL FORM, BUT THIS IS WHAT WILL BE USED AT TPS.

DAILY/INITIAL FLIGHT TEST REPORT

1. AIRCRAFT TYPE	2. SERIAL NUMBER
F-16DM	87-00391

3. CONDITIONS RELATIVE TO TEST

A. PROJECT / MISSION NO	B. FLIGHT NO / DATA POINT	C. DATE
HAVE HOPE / 9	C2 / W/ Biofeedback	12 Sep 2017
D. FRONT COCKPIT *(Left Seat)*	E. FUEL LOAD	F. JON
Subject C	7,960 lbs	MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)*	H. START UP GR WT / CG	I. WEATHER
Test Conductor	29,639 lbs / 39.77%	SKC
J. TO TIME / SORTIE TIME	K. CONFIGURATION / LOADING	L. SURFACE CONDITIONS
1734L / 0.6	CL Tank	23012G18, Dry, 33°C
M. CHASE ACFT / SERIAL NO	N. CHASE CREW	O. CHASE TO TIME / SORTIE TIME
N/A	N/A	N/A

4. PURPOSE OF FLIGHT / TEST POINTS

To collect physiological and cognitive state data with biofeedback available to the test pilot under high G environment IAW HAVE HOPE Test Plan procedures.

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Mission Profile:
Ground Block / Taxi/ Takeoff / GX
Test Set 1 (6, 5, 3, 8, 5, 3, 8, 5, 3) (Each G point held for 10 seconds, 2 second transitions between points)
Rest/Cognitive Test: HR (watch), %HRR (GETAC), Borg, Light Loss, Code Recall, Ops Check, Stroop (words and colors) – call when ready next, read next code
Test Sets 2-4: repeat above

Test Set 1:
Data collection satisfactory. Flew most of profile at or below 10,000 ft for thicker air. Maintained good airspeed on jet, no issues with energy management.
Test Set 2:
Data collection satisfactory. NSTR on G tracking task.
Test Set 3:
Data collection interrupted by loss of TM. Most of cognitive measures were not recorded by control room. Pilot read most of cognitive assessments over VHR once control room directed. NSTR on G tracking
Test Set 4:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Amplifying Comments:
Below is a list of physiological and cogitative state experiences noted by the pilot during execution of the profile.

- Due to late afternoon flight, the sun inhibited the pilots ability to read HUD (G/Airspeed) when passing through westerly heading for approximately 2-3 second intervals. This may have impacted G tracking ability.
- Pilot noted fairly low mental workload and used biofeedback between test sets to assess PC state. Assessed %HRR below 50 and did not need to slow down. Ready in min rest time.
- Pilot noted poor peroformance in random code recall. Much worse than centrifuge.
- Finally, as per previous flights, the pilot deemed biofeedback readings as a lower priority when compared to other tasks. For example, the pilot would be more influenced to commence the next test set due to airspace or fuel limitations than due to what the biofeedback stated (Task focus weighed as a greater priority than biofeedback).
- Borg scores showed 4 or less (moderate to easy exertion)

6. RECOMMENDATIONS

R1: Fly one more sortie w/o biofeedback for comparison.

COMPLETED BY	SIGNATURE	DATE
Subject C	Completed by Subject C	12 Sep 2017

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DAILY/INITIAL FLIGHT TEST REPORT

1. AIRCRAFT TYPE	2. SERIAL NUMBER
F-16DM	87-0391

3. CONDITIONS RELATIVE TO TEST

A. PROJECT / MISSION NO	B. FLIGHT NO / DATA POINT	C. DATE
HAVE HOPE / 11	C3 / No Biofeedback	15 Sep 2017
D. FRONT COCKPIT *(Left Seat)*	E. FUEL LOAD	F. JON
Subject C	7,960 lbs	MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)*	H. START UP GR WT / CG	I. WEATHER
Test Conductor	29,639 lbs / 39.77%	SKC
J. TO TIME / SORTIE TIME	K. CONFIGURATION / LOADING	L. SURFACE CONDITIONS
1600Z / 0.6	CL Tank	22012G18, Dry, 31°C
M. CHASE ACFT / SERIAL NO	N. CHASE CREW	O. CHASE TO TIME / SORTIE TIME
N/A	N/A	N/A

4. PURPOSE OF FLIGHT / TEST POINTS

To collect physiological and cognitive state data with biofeedback available to the test pilot under high G environment IAW HAVE HOPE Test Plan procedures.

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Mission Profile:

Ground Block / Taxi/ Takeoff / GX

Test Set 1 (6, 5, 3, 8, 5, 3, 8, 5, 3) (Each G point held for 10 seconds, 2 second transitions between points)

Rest/Cognitive Test: Borg, Light Loss, Code Recall, Ops Check, Stroop (words and colors) – call when ready next, read next code

Test Sets 2-4: repeat above

Test Set 1:

Data collection satisfactory. Flew most of profile at or below 10,000 ft for thicker air. Maintained good airspeed on jet, no issues with energy management.

Test Set 2:

Data collection satisfactory. NSTR on G tracking task.

Test Set 3:

Data collection satisfactory. NSTR on G tracking

Test Set 4:

Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Amplifying Comments:

Below is a list of physiological and cogitative state experiences noted by the pilot during execution of the profile.

- Pilot noted fairly low mental workload. Subjective assessments of fatigue indicated not tired and continued with profile in minimum rest time.
- Pilot noted poor peroformance in random code recall, but improved compared to previous sortie. Still worse than centrifuge.
- Borg scores showed 4 or less (moderate to easy exertion)
- Pilot felt fairly "ahead" of the jet, and used technique of repeating code during G-tracking in attempt to remember better. Worked until a non-standard radio call, airspace management task, etc was encountered and took attention away. Noted – code was forgotten after secondary task was encountered during G-tracking test set

6. RECOMMENDATIONS

R1: Fly final sortie w/ biofeedback for comparison. Should finish w/ 2 sorties w/ biofeedback and 1 w/o.

COMPLETED BY	SIGNATURE	DATE
Subject C	Completed by Subject C	15 Sep 2017

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DAILY/INITIAL FLIGHT TEST REPORT	1. AIRCRAFT TYPE F-16DM	2. SERIAL NUMBER 87-0391

3. CONDITIONS RELATIVE TO TEST

A. PROJECT / MISSION NO HAVE HOPE / 13	B. FLIGHT NO / DATA POINT C4 / W/ Biofeedback	C. DATE 18 Sep 2017
D. FRONT COCKPIT *(Left Seat)* Subject C	E. FUEL LOAD 7,960 lbs	F. JON MT17A200
G. REAR COCKPIT *(Right Seat and rest of crew)* Test Conductor	H. START UP GR WT / CG 29,639 lbs / 39.77%	I. WEATHER SKC
J. TO TIME / SORTIE TIME 1600Z / 0.6	K. CONFIGURATION / LOADING CL Tank	L. SURFACE CONDITIONS VRB 06, Dry, 29°C
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A

4. PURPOSE OF FLIGHT / TEST POINTS

To collect physiological and cognitive state data with biofeedback available to the test pilot under high G environment IAW HAVE HOPE Test Plan procedures.

5. RESULTS OF TESTS *(Continue on reverse if needed)*

Mission Profile:
Ground Block / Taxi/ Takeoff / GX
Test Set 1 (6, 5, 3, 8, 5, 3, 8, 5, 3) (Each G point held for 10 seconds, 2 second transitions between points)
Rest/Cognitive Test: HR (watch), %HRR (GETAC), Borg, Light Loss, Code Recall, Ops Check, Stroop (words and colors) –
After rest: read Biofeedback [HR (watch), %HRR (GETAC), Borg] - call when ready next, read next code
Test Sets 2-4: repeat above

Test Set 1:
Data collection satisfactory. Flew most of profile at or below 10,000 ft for thicker air. Maintained good airspeed on jet, no issues with energy management.
Test Set 2:
Data collection satisfactory. NSTR on G tracking task.
Test Set 3:
Data collection satisfactory. NSTR on G tracking
Test Set 4:
Profile flown satisfactorily. Data collection satisfactory. See amplifying comments section for specific pilot related physiological and cognitive assessments.

Amplifying Comments:
Below is a list of physiological and cogitative state experiences noted by the pilot during execution of the profile.

- Pilot noted slightly more light loss and more discomfort in left arm, potentially due to compound effects of continuous sorties
- Used biofeedback between test sets and noticed %HRR continuously around 30-40%.
- Did not feel extremely fatigued and due to low %HRR pilot continued subsequent test sets.
- Pilot noted fairly low mental workload. Subjective assessments of fatigue indicated not tired and continued with profile in minimum rest time.
- Noted much improved performance in random code recall, due to learning effect of flying several times in past 7 days and using technique of repeating code in mind during g-tracking. Was able to still rememeber despite secondary tasks involved during g-tracking.
- Borg scores showed 4 or less (moderate to easy exertion)

6. RECOMMENDATIONS

R1: HAVE HOPE data collection complete!

COMPLETED BY	SIGNATURE	DATE
Subject C	Completed by Subject C	18 Sep 2017

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Appendix O – Phase 3 and 4 Test Cards

Viper Data Card

JOKER	BINGO
3.0	2.0

DATE	JON	BRIEF	STEP	START	√IN	TAXI	T/O	LAND	LAND NLT
18-Sep-17	998TMP00	0700	0800	0830	0845	0845	0900		

UHF	VHF	TM	TANKER C/S	FREQ	TRACK	ALT	TCN
233.600	123.350	4630.5	N/A				

CALLSIGN	PILOTS	TAIL #	OPS #	IFF	TCN	SADL/IDM	STN	FCR/SCH
Ammo 81	Hijack/Crunch	391	2162-1					

STPT	CRIPTION	LATITUDE	LONGITUDE	ELEV	Dist	TOS
1	Shadow Ramp (B/E)	N34 54.8000	W117 53.9000	2,312'		

Overview

2. Ground Block	Ensure comms with control room and recorder **HRR, BORG, Code, Ops Checklist, Stroop** Set MSL & ALOW, Test Anti-G Button
3. T/O, and G-Ex	SI Check at 8k MSL **State HRR and Borg following G-ex**

With BIOFEEDBACK

Aircaft Limits

< 7Gs until centerline tank empty

Setup: 14k ft PA A/S: .92M

4. Test Set 1: 6, 5, 3, 8, 5, 3, 8, 5, 3
Rest: HRR, BORG, LL, Code, Ops Checklist, Stroop

5. Test Set 2: 6, 5, 3, 8, 5, 3, 8, 5, 3
Rest: HRR, BORG, LL, Code, Ops Checklist, Stroop

6. Test Set 3: 6, 5, 3, 8, 5, 3, 8, 5, 3
Rest: HRR, BORG, LL, Code, Ops Checklist, Stroop

7. Test Set 4: 6, 5, 3, 8, 5, 3, 8, 5, 3
Rest: HRR, BORG, LL, Code, Ops Checklist, Stroop

8. RTB

Test Limits

Test Sets > 5,000 ft AGL
Max dive angle 15 degrees
No more than 8 Manuevers at > 7Gs

LAKEBEDS
05L/23R
05R/23L
07/25
09/27
15/33
12L/30R
12R/30L
06/24N
06/24S
04 OVRN
PAD 18
R-11/29
R-02/20
17L/35R
17C/35C
17R/35L
18L/36R
~~18C/36C~~
18R/36L
D Exit

FREQS		
1	ATIS	269.9
2	CONFORM	304.0
3	GROUND	125.4
4	TOWER	318.1
5	SPORT	340.7
6	J-ISB	348.7
7	J-OWENS	322.3
8	J-SALINE	256.8
9	J-PMINT	291.6
10	AAR	354.4
11	Low Lvl	315.9
12	NID	340.2
13	J-PMD	363.0
14	PMD	317.6
20	SOF	308.7
TPS Ops		301.5 / 142.2

LIMITS	
Config	1
C/CM	DG
a/s	
sym	
asy	

TAIL	FORM F	T/O GW		NO FUEL WEIGHT		EJ NO FUEL WT		EMER JETT ON T/O Opt / Hi Key / Lo Key	Config
391	2/21/17	29.0		21.7		21.3		225 / 12.8 / 7.1	C1
Tail	AB/Mil	ACCEL	ROT	TO	DIST	APP	DIST	SFO STORES	
391	Mil	126	148	158	3.2	172	3.9/7.1	2K	C1

Have Hope | F-16 | Data | Joker/Bingo 3/2

1 - 10 Borg Rating of Perceived Exertion Scale	
0	Rest
1	Really Easy
2	Easy
3	Moderate
4	Sort of Hard
5	Hard
6	
7	Really Hard
8	
9	Really, Really, Hard
10	Maximal: Just like my hardest race

HRR
Borg
Light Loss
Code
Ops Check
Stroop

LAKEBEDS
05L/23R
05R/23L
07/25
09/27
15/33
12L/30R
12R/30L
06/24N
06/24S
04 OVRN
PAD 18
R-11/29
R-02/20
17L/35R
17C/35C
17R/35L
18L/36R
~~18C/36C~~
18R/36L
D Exit

KCAS	MACH	Symmetric	Assymetric	AOA	ROLL
600	1.6	7.0 / -2.5	5.5 / -1.0	LIM	360
CL Tank Empty		(9.0 / -3.0)	(6.0 / -1.0)		

Stroop and Code attached as separate page

PMD	92X	198°/20	200#	8K/0.45M
NID	53X	355°/48	400#	20K/0.55M
RIV	77X	138°/68	500#	24K/0.60M
NTD	43X	218°/78	600#	28K/0.65M

TOPS	SPORT	WX	RAPTOR	TPS	416th
5-4260	7-3928	7-4472	5-4539	7-4176	7-2555

Code for Flying

HAVE HOPE RANDOM CODE

GROUND BLOCK				
PURPLE	●	6	4	6
Test Set 1				
BLUE	●	1	9	9
Test Set 2				
ORANGE	▲	1	1	9
Test Set 3				
BLUE	▲	4	7	3
Test Set 4				
RED	●	2	3	4

Stroop for Flying

HAVE HOPE STROOP TASK

1	YELLOW	RED	BLUE	RED	GREEN	ORANGE
2	RED	PURPLE	GREEN	PURPLE	BLUE	YELLOW
3	ORANGE	RED	RED	BLUE	BLUE	YELLOW
4	ORANGE	GREEN	YELLOW	PURPLE	YELLOW	YELLOW
5	BLUE	PURPLE	BLUE	ORANGE	BLUE	BLUE
6	RED	RED	PURPLE	BLUE	BLUE	RED
7	GREEN	YELLOW	BLUE	ORANGE	BLUE	PURPLE
8	GREEN	GREEN	RED	PURPLE	YELLOW	GREEN
9	RED	YELLOW	PURPLE	YELLOW	GREEN	RED
10	GREEN	BLUE	ORANGE	BLUE	BLUE	RED
11	BLUE	ORANGE	GREEN	RED	PURPLE	GREEN
12	BLUE	PURPLE	ORANGE	YELLOW	ORANGE	ORANGE
13	ORANGE	ORANGE	YELLOW	PURPLE	ORANGE	ORANGE
14	ORANGE	GREEN	YELLOW	RED	RED	YELLOW
15	GREEN	YELLOW	BLUE	ORANGE	PURPLE	RED
16	BLUE	YELLOW	GREEN	GREEN	RED	ORANGE
17	PURPLE	PURPLE	GREEN	PURPLE	PURPLE	ORANGE
18	ORANGE	GREEN	YELLOW	RED	GREEN	PURPLE
19	PURPLE	BLUE	GREEN	RED	PURPLE	RED
20	PURPLE	GREEN	YELLOW	PURPLE	GREEN	GREEN

Code for TC / TD

HAVE HOPE RANDOM CODE

GROUND BLOCK				
PURPLE	●	6	4	6
Test Set 1				
BLUE	●	1	9	9
Test Set 2				
ORANGE	▲	1	1	9
Test Set 3				
BLUE	▲	4	7	3
Test Set 4				
RED	●	2	3	4

Stroop for TC / TD

HAVE HOPE STROOP TASK

1	YELLOW	RED	BLUE	RED	GREEN	ORANGE
2	RED	PURPLE	GREEN	PURPLE	BLUE	YELLOW
3	ORANGE	RED	RED	BLUE	BLUE	YELLOW
4	ORANGE	GREEN	YELLOW	PURPLE	YELLOW	YELLOW
5	BLUE	PURPLE	BLUE	ORANGE	BLUE	BLUE
6	RED	RED	PURPLE	BLUE	BLUE	RED
7	GREEN	YELLOW	BLUE	ORANGE	BLUE	PURPLE
8	GREEN	GREEN	RED	PURPLE	YELLOW	GREEN
9	RED	YELLOW	PURPLE	YELLOW	GREEN	RED
10	GREEN	BLUE	ORANGE	BLUE	BLUE	RED
11	BLUE	ORANGE	GREEN	RED	PURPLE	GREEN
12	BLUE	PURPLE	ORANGE	YELLOW	ORANGE	ORANGE
13	ORANGE	ORANGE	YELLOW	PURPLE	ORANGE	ORANGE
14	ORANGE	GREEN	YELLOW	RED	RED	YELLOW
15	GREEN	YELLOW	BLUE	ORANGE	PURPLE	RED
16	BLUE	YELLOW	GREEN	GREEN	RED	ORANGE
17	PURPLE	PURPLE	GREEN	PURPLE	PURPLE	ORANGE
18	ORANGE	GREEN	YELLOW	RED	GREEN	PURPLE
19	PURPLE	BLUE	GREEN	RED	PURPLE	RED
20	PURPLE	GREEN	YELLOW	PURPLE	GREEN	GREEN

	GND Block	Test Set 1	Test Set 2	Test Set 3	Test Set 4	CARD#
W	17	19	16	8	20	
C	8	12	1	9	2	

2. Ground Block

Configuration: A/R

Data Procedure: Record Ground Block Data

Last week:	Rest	Hydration	(1-10) 1 worst
Last 24 hrs:	Rest	Hydration	10 Best

1. DAS SYSTEM CHECK COMPLETE
   (FCP) DATA ON
   (RCP) DATA RECORDING (CHECK PERCENTAGE COUNTING DOWN!)
   TM Check / Control Room Check
2. EVENT MARKER _____
3. PILOT READ THE FOLLOWING:
   A. DATE:
   B. A/C TAIL # 391, CALL SIGN , OPS #
   C. CREW NAMES
   D. MISSION TITLE **HAVE HOPE** **With** **BIOFEEDBACK**
4. Prior to taxi, pilot reads ground code
5. Ground Run
   Time Hack: __________ *based on HUD/TM

TELLL TP to complete ground cog tasks as fast as he can

With Biofeedback, Record HR/%HRR		Borg: ________
Garmin	%HRR	Gs: ________

Code

PURPLE	●	6	4	6

OPS Checklist Time

1. Fuel – Check quantity/transfer/balance
2. FUEL QTY SEL knob - NORM
3. Oxygen system - Check
4. Cockpit pressurization - Check
5. Engine instruments - Check
6. HYD PRESS A & B - Check Time

NEXT: 3. T/O, and G-Ex

3. T/O, and G-Ex

SETUP:	Limits
14,000 ft + 1000ft ft PA M .92	7 Gs until centerline empty
Mil Power	A/S < .95 Mach

Stroop			Time
8	Color	Purple Purple Blue Green Blue Yellow	
17	Word	Purple Purple Green Purple Purple Orange	

ALOW & MSL Set? Anti-G Button Tested?

T/O time _________

Confirm Alt at 8k MSL____

G-Ex 4Gs

SI Check	G	M	Alt

	With Biofeedback, Record HR/%HRR		Borg
1	Garmin	%HRR	

G-Ex 6Gs

	With Biofeedback, Record HR/%HRR		Borg
2	Garmin	%HRR	

Next is Test Run at 14-15k ft PA .92M A/S entry

Confirm:

Centerline tank empty

Comm Flow (with/without Bio) at rest
   with bio: TP reads bio before and after each test set
   with and without: borg, code, Ops check, stroop

Timer Ready

Recording Ready

TP & TC Ready: TP READS CODE 2

Start Countdown

NEXT: 4. Test Set 1

4. Test Set 1

SETUP:	Limits
14k-15,000 ft PA A/S .92M	Centerline Tanks Empty
MIL/MAX POWER as required	< 1.0 M

Test Set Gs 6, 5, 3, 8, 5, 3, 8, 5, 3

EVENT MARKER:

TP start garmin watch
TP "TP Ready, HR is ___, Code is ______"
TC "Ready"
TD "Ready Test Set 1"

Timer Starts Test Set Recording "5, 4... Hack" Timer starts Master at "Hack"

Pilot Executes 6 Gs at "2"

Start Stop Watch for Rest at "Hack"

EVENT MARKER:

Notes

NEXT: Physical Cog Card Test Set 1

4

Physical Cog Card Test Set 1

Rest is 60s Minimum

At Start of Rest TP Calls "HRR #, Borg #, Code Recal ###, Ops"

With Biofeedback, Record HR/%HRR	Borg	Light Loss
Garmin %HRR		

Test Set 1 Code

BLUE	●	1	9	9

Time

OPS Checklist
1. Fuel – Check quantity/transfer/balance
2. FUEL QTY SEL knob - NORM
3. Oxygen system - Check
4. Cockpit pressurization - Check
5. Engine instruments - Check
6. HYD PRESS A & B - Check

Time

Stroop line	color/word		Time
12	Color	Blue Red Green Blue Purple Yellow	
19	Word	Purple Blue Green Red Purple Yellow	

When TP Is Rested
TD "Read Next Code, HRR (if with bio)"
TP "Code is ____"
or at 7s Left (if rested before 60s min time) start recording

With Biofeedback	Borg
Garmin %HRR	

Cog Time

Rest Time

NEXT: 5. Test Set 2

4a

5. Test Set 2

SETUP:	Limits
14k-15,000 ft PA A/S .92M	Centerline Tanks Empty
MIL/MAX POWER as required	< 1.0 M

Test Set Gs 6, 5, 3, 8, 5, 3, 8, 5, 3

EVENT MARKER:

TP start garmin watch
TP "TP Ready, HR is ___, Code is ______"
TC "Ready"
TD "Ready Test Set 2"

Timer Starts Test Set Recording "5, 4... Hack" Timer starts Master at "Hack"

Pilot Executes 6 Gs at "2"

Start Stop Watch for Rest at "Hack"

EVENT MARKER:

Notes

NEXT: Physical Cog Card Test Set 2

5

Physical Cog Card Test Set 2

Rest is 60s Minimum

At Start of Rest TP Calls "HRR #, Borg #, Code Recal ###, Ops"

With Biofeedback, Record HR/%HRR		Borg	Light Loss
Garmin	%HRR		

Test Set 2 Code

ORANGE	▲	1	1	9

Time

OPS Checklist

1. Fuel – Check quantity/transfer/balance
2. FUEL QTY SEL knob - NORM
3. Oxygen system - Check
4. Cockpit pressurization - Check
5. Engine instruments - Check
6. HYD PRESS A & B - Check

Time

Stroop line	color/word		Time
1	Color	Yellow Green Red Yellow Green Blue	
16	Word	Blue Yellow Green Green Red Orange	

When TP Is Rested
TD "Read Next Code, HRR (if with bio)"
TP "Code is ____"
or at 7s Left (if rested before 60s min time) start recording

With Biofeedback		Borg
Garmin	%HRR	

Cog Time

Rest Time

NEXT: 6. Test Set 3

5a

6. Test Set 3

SETUP:	Limits
14k-15,000 ft PA A/S .92M MIL/MAX POWER as required	Centerline Tanks Empty < 1.0 M

Test Set Gs 6, 5, 3, 8, 5, 3, 8, 5, 3

EVENT MARKER:

TP start garmin watch
TP "TP Ready, HR is ___, Code is ______"
TC "Ready"
TD "Ready Test Set 3"

Timer Starts Test Set Recording "5, 4... Hack" Timer starts Master at "Hack"

Pilot Executes 6 Gs at "2"

Start Stop Watch for Rest at "Hack"

EVENT MARKER:

Notes

NEXT: Physical Cog Card Test Set 3

6

Physical Cog Card Test Set 3

Rest is 60s Minimum

At Start of Rest TP Calls "HRR #, Borg #, Code Recal ###, Ops"

With Biofeedback, Record HR/%HRR	Borg	Light Loss
Garmin %HRR		

Test Set 3 Code

BLUE	▲	**4**	**7**	**3**

Time

OPS Checklist

1. Fuel – Check quantity/transfer/balance
2. FUEL QTY SEL knob - NORM
3. Oxygen system - Check
4. Cockpit pressurization - Check
5. Engine instruments - Check
6. HYD PRESS A & B - Check Time

Stroop line		color/word	Time
8	Word	Green Green Red Purple Yellow Green	
9	Color	Yellow Yellow Green Yellow Blue Green	

When TP Is Rested TD "Read Next Code, HRR (if with bio)"
TP "Code is ____"
or at 7s Left (if rested before 60s min time) start recording

With Biofeedback	Borg
Garmin %HRR	

Cog Time

Rest Time

NEXT: 7. Test Set 4

6a

7. Test Set 4

SETUP:	Limits
14k-15,000 ft PA A/S .92M	Centerline Tanks Empty
MIL/MAX POWER as required	< 1.0 M

Test Set Gs 6, 5, 3, 8, 5, 3, 8, 5, 3

EVENT MARKER:

TP start garmin watch
TP "TP Ready, HR is ___, Code is ______"
TC "Ready"
TD "Ready Test Set 4"

Timer Starts Test Set Recording "5, 4... Hack" Timer starts Master at "Hack"

Pilot Executes 6 Gs at "2"

Start Stop Watch for Rest at "Hack"

EVENT MARKER:

Notes

NEXT: Physical Cog Card Test Set 4

7

Physical Cog Card Test Set 4

Rest is 60s Minimum

At Start of Rest TP Calls "HRR #, Borg #, Code Recal ###, Ops"

With Biofeedback, Record HR/%HRR		Borg	Light Loss
Garmin	%HRR		

Test Set 4 Code

RED	●	2	3	4

Time

OPS Checklist

1. Fuel – Check quantity/transfer/balance
2. FUEL QTY SEL knob - NORM
3. Oxygen system - Check
4. Cockpit pressurization - Check
5. Engine instruments - Check
6. HYD PRESS A & B - Check

Time

Stroop			Time
20	Word	Purple Green Yellow Purple Green Green	
2	Color	Green Purple Red Blue Purple Purple	

TD "Test Run Ended"
TC Stop Master watch

Cog Time

Total Time

TC "RTB when ready"

GROUND
Stop Recording

TP "Control Room Released"
SI Off

TC Retrieve DAS card

NEXT: Wake up TC, Rest and RTB

7a

Timer 1 Card 1

Procedures

1. Start stop watch 1 at first hack to start all test runs
2. Start stop watch 2 at rest hack
3. hit lap at each event start/stop (two laps)
4. Note Cog total time (at end of stroop)
5. stop watch 2 at end of rest (hack for test set)
6. Stop watch 1 at last cog finish

Hack times

Start Test Run Time (TM/HUD time) ____________

Ground Block

Notes

	Time
Code	
Ops √	
Stroop C	
Stroop W	

Test Set 1

	Time
Code	
Ops √	
Stroop C	
Stroop W	

Cog time: __________

Rest Time: __________

Test Set 2

	Time
Code	
Ops √	
Stroop C	
Stroop W	

Cog time: __________

Rest Time: __________

Timer Card 2

Test set 3

Notes

	Time
Code	
Ops √	
Stroop C	
Stroop W	

Cog time: __________

Rest Time: __________

Test set 4

	Time
Code	
Ops √	
Stroop C	
Stroop W	

Cog time: __________

Rest Time: __________

Stop Test Run time (HUD/TM) Total Time

Notes

Appendix P – MATLAB Code

This is a MATLAB code that takes the heart rate and normal acceleration values from the centrifuge and plots them together. The HR data is filtered to reduce noise with a moving average filter that uses a box size of 2500. The Nz is also filtered with a moving average filter but of only a 20 box size. Data is then plotted with two different Y axes but the same X axis.

FugePlot.m

```
close all
T=Time;
HR=HRATE;
Nz=ACCEL;
%% Filter Parameters
windowSize = 2500;
b = (1/windowSize)*ones(1,windowSize);
a = 1;
x = HR;
HRfilt = filter(b,a,x);
%% Filter Parameters
windowSize = 20;
c = (1/windowSize)*ones(1,windowSize);
d = 1;
y = Nz;
NZfilt = filter(c,d,y);
%% the max and min HRs for each subject
% PerHRR1=[64,197];
% PerHRR2=[52,199];
% PerHRR3=[52,195];
% PerHRR4=[60,185];
 PerHRR5=[50,198];
%% converting HR to HRR, one equation for each subject
% HRR=((HRfilt-PerHRR1(1))/(PerHRR1(2)-PerHRR1(1)))*100;
% HRR=((HRfilt-PerHRR2(1))/(PerHRR2(2)-PerHRR2(1)))*100;
% HRR=((HRfilt-PerHRR3(1))/(PerHRR3(2)-PerHRR3(1)))*100;
% HRR=((HRfilt-PerHRR4(1))/(PerHRR4(2)-PerHRR4(1)))*100;
 HRR=((HRfilt-PerHRR5(1))/(PerHRR5(2)-PerHRR5(1)))*100;
%% Plotting %HRR vs Time and Nz vs Time
plot(T,HR)
hold on
plot(T,HRfilt,'k')
figure()
[hAx,hLine1,hLine2] = plotyy(T,HRR,T,NZfilt);
title('Subject B W/O Biofeedback')
xlabel('Time (sec)')
tspan=[250 1050];
xlim(hAx(2),tspan)
xlim(hAx(1),tspan)
ylabel(hAx(1),'%HRR Based on Centrifuge ECG') % left y-axis
ylabel(hAx(2),'Nz') % right y-axis
ylim(hAx(2),[1.5 8.5])
ylim(hAx(1),[0 100])
```

This is a code to plot %HRR values based on the Garmin watch heart rate data against the Nz seen in flight. HR values are converted into %HRR based on each subjects max and min HR vaues.

HRR_VS_Nz_Plotter.m

```
%% Seting up some parameters to make import easier
%  won't need this step if import doesn't have two lines of header
t_sec=GarminTime(3:end);
HR=HeartRate(3:end);
%% HR Plotter
Nz_Time=Delta_Irig-Delta_Irig(1);
HR_Time=t_sec-t_sec(1);
% HR_Time=HR_Time-50; %offset if times don't match up perfectly
%% HR to HRR, select which subject below
% %Subject A
% maxHR=197;
% minHR=64;
% %Subject B
maxHR=199;
minHR=52;
% %HRR from HR subject C
% maxHR=195;
% minHR=52;
HRR=((HR-minHR)./(maxHR-minHR)).*100;
%% Generate Plots
close all
figure(1)
[hAx,hLine1,hLine2] = plotyy(HR_Time,HRR,Nz_Time,NZ);
title('Subject B W/ Biofeedback')
xlabel('Time (sec)')
tspan=[400 1650];
xlim(hAx(2),tspan)
xlim(hAx(1),tspan)
ylabel(hAx(1),'%HRR Based on Garmin') % left y-axis
ylabel(hAx(2),'Nz') % right y-axis
ylim(hAx(2),[1.0 8.5])
hAx(2).YTick=[1:1:8];
ylim(hAx(1),[0 100])
hAx(1).YTick=[0:10:100];
%figure(2)
%plotyy(HR_Time,HR,Nz_Time,NZ)
```

A code to generate error scores for the flights. It measures how far out of the tolerance the pilot's G was and for how long. It then multiplies those numbers together to get the error score. It also creates a plot showing the ideal profile, the tolerance interval, and the flown profile overlaid.

NzAcurracy.m

```
%% First Select the start time of the profile
start_index=input('index of start time for data set');
%start_index=1;
%% Individual Profile will be parsed out of data
Executed_Profile=NZ(start_index:start_index+2119);
Executed_Profile=Executed_Profile';
Start=Delta_Irig(start_index);
End=Delta_Irig(start_index)+106-0.05;
Time=[Start:0.05:End];
%% Generate the ideal profile to grade against
SampleRate=0.05;
N10=10/SampleRate;
N2=2/SampleRate;
SixGs=linspace(6,6,N10);
SixToFive=linspace(6,5,N2);
FiveGs=linspace(5,5,N10);
FiveToThree=linspace(5,3,N2);
ThreeGs=linspace(3,3,N10);
ThreeToEight=linspace(3,8,N2);
EightGs=linspace(8,8,N10);
EightToFive=linspace(8,5,N2);
PerfectProfile=[SixGs SixToFive FiveGs FiveToThree ThreeGs...
    ThreeToEight EightGs EightToFive FiveGs FiveToThree...
    ThreeGs ThreeToEight EightGs EightToFive FiveGs...
    FiveToThree ThreeGs];
UpperProfile=PerfectProfile+.2;
LowerProfile=PerfectProfile-.2;
%% Plot the data agianst the ideal profile with tolerance limits
close all
plot(Time,PerfectProfile,'k-.')
hold on
plot(Time,UpperProfile,'k--')
plot(Time,LowerProfile,'k--')
plot(Time,Executed_Profile,'k')
%% Error Determination
Difference=abs(PerfectProfile-Executed_Profile);
N=1;
while N<=8
    Begin=(200*N)+1+(40*(N-1));
    End=(200*N)+40+(40*(N-1));
    Difference(Begin:End)=0;
    N=N+1;
end
N=1;
while N<=length(Difference)
    if Difference(N)<0.2
        Difference(N)=0;
    end
    N=N+1;
```

```
end
G_Tracking_Score=sum(Difference)*0.05
%% Plotting Errors
% figure()
% plot(PerfectProfile)
% hold on
% plot(Difference)
% plot(Executed_Profile)
% plot(UpperProfile)
% plot(LowerProfile)
```

A code to generate an error score for the tracking done in the centrifuge. This takes the target location and adds a tolerance interval of 0.2G then determines how far out of that interval the commanded G was and for how long. The two values are multiplies together to get the error score. The target location, tolerance interval, and commanded G are then all plotted overlaid on the same figure.

TrackingPlot.m

```
close ALL
Time=VarName1;
TargetLocation=VarName2;
PipperLocation=VarName3;
plot(Time,PipperLocation,'k')
hold on
plot(Time,TargetLocation,'k-.')
TargetUp=TargetLocation+0.2;
TargetDown=TargetLocation-0.2;
plot(Time,TargetUp,'k--')
plot(Time,TargetDown,'k--')
% Error=abs(TargetLocation-PipperLocation);
% plot(Time,Error,'r')
% MeanError=mean(Error)
%% Error Determination
Difference=abs(TargetLocation-PipperLocation);
% N=1;
% while N<=8
%     Begin=(200*N)+1+(40*(N-1));
%     End=(200*N)+40+(40*(N-1));
%     Difference(Begin:End)=0;
%     N=N+1;
% end
N=1;
while N<=length(Difference)
    if Difference(N)<0.2
        Difference(N)=0;
    end
    N=N+1;
end
G_Tracking_Score=sum(Difference)*0.05
clear
```

Appendix Q – Lessons Learned

1. When planning for Electromagnetic Interference Compatibility (EMIC) testing with F-16 Maintenance, ensure that the specific configuration matches the loadout on the EMIC aircraft. As well, plan on EMIC testing at least 1 month prior to the first flight of the test program to allow the System Program Office (SPO) the necessary time to complete paperwork for a flight release. When coordinating the EMIC with Maintenance, ensure they know the jet must be in a fully configured and flyable state so that a complete ground run can be accomplished. Our jet had no O_2 in the aircraft for our first attempt at the EMIC.

2. When accomplishing testing with human subjects ensure to comply with proper protocols. Thorough lead-time must be put into coordinating an Institutional Review Board (IRB). Our team had points of contact at the 711th Human Performance Wing (711 HPW) and Naval Medical Research Unit Dayton (NAMRU-D). Additionally, all test team members had to complete Collaborative Institutional Training Initiative (CITI) Program in order to be approved to conduct human testing on subjects. We were both approved testers and test subjects. The training consisted of 20 computer-based trainings (CBTs) with module tests totaling three to four hours culminating in a completion certificate.

3. When coordinating to use the KBRWyle centrifuge ensure to contact them and get on their schedule early. We booked our August 2017 testing back in November 2016 during initial HAVE HOPE trials for the Air Force Institute of Technology (AFIT) and 711 HPW. Additionally, ensure you're specific with your requests for the type of testing needed and determine if their current capabilities can meet your required data. They are a government contractor so any configuration changes or new capabilities outside of their baseline mission may require further funding and/or coordination.

4. Ensure early and often coordination with the F-16 SPO anytime you plan to place any new test hardware inside the cockpit. None of our hardware was wired to the aircraft, but still required coordination up to one year in advance to ensure all necessary approvals, cleared-to-fly, and airworthiness was complied with. Hardware often requires windblast testing, EMIC, AFE hanging harness, and cyber approval. Ultimately, you are looking to obtain a Military Flight Release (MFR) for specific aircraft tail numbers and specific configurations.

5. Ensure thorough coordination with your customer, project sponsor, and hardware developer. We conducted bi-monthly telecoms with our 711th HPW team and found it extremely necessary.

Vita

Major Michael S. Fritts is currently a candidate in the Joint Air Force Institute of Technology (AFIT) and USAF Test Pilot School (TPS) Program. Each year the Air Force TPS Selection Board selects two or more Air Force officers for this combined program in which participating students are awarded dual diplomas. He entered AFIT in September 2015 and completed focus areas of aircraft stability and control and human systems engineering as well as all Masters of Science (MS) coursework in 15 months.

Major Fritts completed a portion of this thesis requirement, departed AFIT in December 2016 without a degree, and entered TPS at Edwards AFB, CA for a 1-year program where he designed and flew a test management project that was subsequently incorporated into this MS thesis. He graduated TPS in December 2017 as the class leader of class 17A and was awarded an MS in Flight Test Engineering from Air University. Upon successful defense of this AFIT thesis he will be awarded an MS in Aeronautical Engineering from AFIT, thus completing the Joint AFIT-TPS Program.

Major Fritts earned his commission from the Massachusetts Institute of Technology (MIT) Air Force Reserve Officer Training Corps (AFROTC) Program in 2005. Upon graduation, Major Fritts attended Specialized Undergraduate Pilot Training and Introduction to Fighter Fundamentals (IFF) at Columbus AFB, MS where he was awarded the William Leverette Award as the top graduate in the T-37B phase, Academic and Top Gun Awards for the T-38C phase, and finished IFF as a Distinguished Graduate. He attended the F-15C B-Course at Tyndall AFB, FL where he earned the Outstanding Academic Graduate Award and assignment to the 71st Fighter Squadron, Langley AFB, VA. During this assignment Major Fritts served as Electronic Combat Officer, Chief of Scheduling, and upgraded to F-15C Flight Lead while flying over 20 missions and 100 hours in support of Operation NOBLE EAGLE, providing protection to POTUS, the Space Shuttle, and other National Security Assets. He subsequently transitioned to the F-22 and upgraded to Flight Lead while serving as Chief of Stan/Eval for the 94th Fighter Squadron. Upon reassignment to Joint Base Elmendorf-Richardson, AK, Major Fritts upgraded to F-22 Mission Commander, and served as the Aircrew Flight Equipment (AFE) Flight Commander for the 3rd Operations Support Squadron. During this time he acted as Mission Commander during numerous RED FLAG-ALASKA exercises and deployed to Southwest Asia as part of a 6-month F-22 Theater Security Package (TSP). Major Fritts applied and was accepted to the AFIT-TPS Program in 2014.

Upon graduation from AFIT, Major Fritts will be assigned to the 40th Flight Test Squadron at Eglin AFB, FL where he will be an experimental test pilot performing development test for the F-15C and F-15E. He has accumulated over 1450 total hours in 33 aircraft including the T-37B, T-38C, SGS-233A, AT-6, R-44, GROB-103, DG-1000, L-39C, ASK-21, LJ-25, CM-170, CT-114, CH-146, UH-60L, U-6A, F/A-18F, B777, A320, CV-22B, MiG-21, AN-32, Mi-17, HU-16, C-12C, E-300B, KC-135, TT-1, MQ-9A, C-17, NF-16D, F-16D, F-15C/D, and F-22.

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14. ABSTRACT

A four-phase, chronological, and build-up approach was implemented that commenced with basic hardware testing in a centrifuge and culminated in flights augmented by real-time biofeedback displays. A prototype Portable Electrocardiogram Unit (PECGU) was designed and proven to accurately measure heart rate (HR) and display percent heart rate reserve (%HRR).
Results showed that %HRR was not a sole predictor of cognitive state. Cognitive responses indicated some correlation with %HRR, but were influenced by environment (centrifuge vs. flight). Subjective perceived exertion levels did not show statistically significant changes during test with biofeedback. A G-tracking task was evaluated during centrifuge and flight tests. One of four subjects showed statically significant improvement during the centrifuge while one of three subjects statistically improved during airborne G-tracking.
This research marked the first time pilot HR was accurately measured and processed in flight, yielding a real-time biofeedback display. Overall, results could not be characterized by a single HR metric. A wide range of biosensors is needed to define operator physiological and cognitive (PC) state. There is hope for future development of an individualized, all-inclusive, and data-driven complex biofeedback algorithm, which ultimately presents a streamlined and intuitive PC state index with potentially tremendous enduring benefits to the warfighter.

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