An Ecological Perceptual Aid for Precision Vertical Landings

by

Cristin Anne Smith

B.S. Astronautical Engineering
United States Air Force Academy, 2004

Submitted to the Department of Aeronautics and Astronautics
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Author ....
Department of Aeronautics and Astronautics
May 18, 2006

Certified by ....
Mary L. Cummings
Assistant Professor of Aeronautics and Astronautics
Thesis Supervisor

Certified by ....
Laura M. Forest
Human-Machine Collaboration Engineer
The Charles Stark Draper Laboratory, Inc.
Thesis Supervisor

Accepted by ....
Jaime Peraire
Chairman, Department Committee on Graduate Students

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Abstract

Pilots of vertical landing vehicles face numerous control challenges which often involve the loss of outside visual perceptual cues or the control of flight parameters within tight constraints. These challenges are often associated with a high mental workload, therefore, a precision landing aid that addresses and helps to mitigate these challenges, and reduce mental workload is needed. To address this need, a cognitive task analysis identified specific situation awareness requirements for the design of a vertical landing aid in order to reduce the mental steps required during a vertical landing. From these requirements, a new vertical landing decision aid, known as the Vertical Altitude and Velocity Indicator (VAVI) was designed, which displays altitude and vertical speed information in an integrated form including the display of flight parameter safety constraints. The display instrument takes advantage of direct-perception interaction by leveraging ecological perception and emergent features to provide quick perception and comprehension of critical flight parameters in an integrated fashion.

To test the effectiveness of the VAVI for vertical landing and hover performance, an experiment was conducted in which participants flew a simulated Harrier vertical landing flight profile using Microsoft Flight Simulator (MSFS) 2004. Participants were recruited for their helicopter pilot experience or PC flight simulator experience. Two heads-up displays were implemented: one which included the VAVI, and another which displayed altitude and vertical speed information consistent with operational V/STOL aircraft head-up displays. A 2x2 ANOVA design was utilized in which the heads-up display was a between-subjects factor and flight task, which included hovering and landing, was a within-subjects factor. Participants participated in two test scenarios which involved hovering at a specified altitudes and descending using either a static or dynamic vertical speed heuristic.

The VAVI showed statistically significantly better vertical speed control performance over the conventional display of altitude and vertical speed. Similarly, though not statistically significant, other dependent variables used to measure landing performance as well as precision hovering consistently resulted in better performance with the VAVI. A subjective workload survey indicated that the VAVI caused less workload across all experimental tasks, indicating that the VAVI does help to remove some of the demanding cognitive processes currently associated with vertical landing and hover operations. Future design and implementation issues are discussed.

Thesis Supervisor: Mary L. Cummings
Title: Assistant Professor of Aeronautics and Astronautics

Thesis Supervisor: Laura M. Forest
Title: Human-Machine Collaboration Engineer
The Charles Stark Draper Laboratory, Inc.

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Cristin A. Smith, 2d Lt, USAF

May 18, 2006

Assignment

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Cristin A. Smith, 2d Lt, USAF
May 18, 2006

Contents

Chapter 1

Introduction

The need for vertical precision landing capability has long been recognized for military, space, and commercial applications. While the first vertical takeoff and landing aircraft, such as balloons and airships were difficult to maneuver, current technology has revolutionized air and spacecraft vertical flight and the future of this capability is promising. The advantages of vertical flight do not come without unique challenges however. Specifically, vertical operations such as hovering and precision landing are difficult tasks that can be confounded by various aerodynamic effects or a loss of visual cues. This is a challenge because for vertical precision landings in particular, pilots rely almost completely on perceptual cues external to the cockpit. Precision landing flight displays, however, have not caught up to the promising advances in vertical flight technology.

Aircraft with vertical takeoff and landing capability fall into one of two categories: V/STOL (vertical/short-takeoff and landing) and helicopters. V/STOL aircraft include convertiplanes such as harriers (a vectored-thrust aircraft) and Ospreys (a tilt rotor aircraft) which can fly horizontally with the same effectiveness as conventional aircraft, but have the capability to takeoff and land vertically. Helicopters are rotorcrafts that derive their lift from rotating blades regardless of the phase of flight. The Harrier and V-22 Osprey are the only operational V/STOL aircraft used today, with the Joint Strike Fighter (JSF) soon to become the next generation V/STOL aircraft.

In the space domain, the Apollo Lunar Module (LM) was designed for vertical landings and takeoffs on the Moon. During the Apollo era (1960s-1972) there were no high fidelity maps of the Moon and thus a vertical landing was exploited to ensure there were no hazards in the landing region. Current studies indicate that future missions to the Moon, and later to Mars, will most likely have a similar vertical landing trajectory [1].

The vertical descent to landing represents one of the most difficult aircraft maneuvers that hover aircraft pilots face. It was also one of the most challenging and unique aspects of landing on the Moon. Lunar and earth vertical landings exhibit several similar perceptual challenges with few tools to assist the pilot with such tasks as hovering and maintaining a safe descent rate, while sustaining an accurate awareness of the present state of the vehicle. One of the primary technologies available to air and spacecraft pilots for making a precision landing, especially in low visibility situations, are integrated flight instrument displays. Integrated flight displays provide critical vehicle attitude and rate information with a higher degree of precision than the human can discern through visual and vestibular cues. This thesis examines the human factors challenges of precision vertical landing, for both air and space domains. While takeoff is also an important flight phase, this thesis focuses specifically on the challenges of precision vertical landing. A new precision landing aid that leverages ecological perception is introduced and its effectiveness tested and discussed for application in both domains.

1.1 Motivation

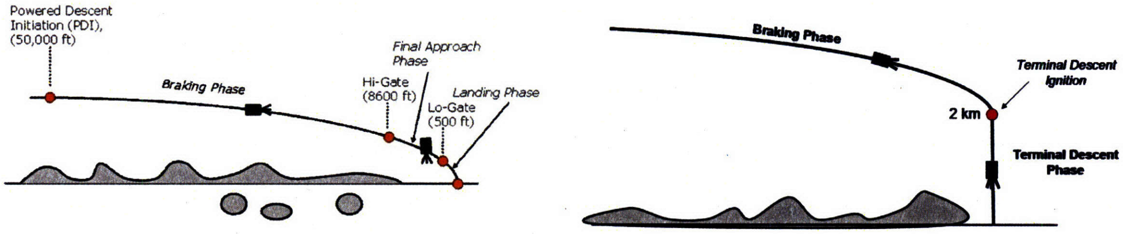
1.1.1 Aircraft Vertical Takeoff and Landing Capability Advantages

V/STOL aircraft and rotorcraft have many advantages in today's military as well as first response and commercial applications. The ability to operate from rapidly constructed expeditionary airfields, forward sites such as roads, various amphibious ships, and damaged conventional airfields, enables dedicated close air support [2].

In addition, not requiring a runway enables V/STOL aircraft to reach very exact areas for the purposes of search and rescue operations and airlift or airdrop. With urban warfare becoming increasingly more common, the ability to reach tight spaces such as the tops of buildings or roads between large structures is even greater. In these situations, the ability to vertically land precisely and safely becomes a critical factor in the success of such missions. In non-military applications, helicopters and V/STOL aircraft are advantageous for their efficient use of airspace, reduction in the noise footprint, and the ability to land in weather conditions prohibitive for fixed-wing aircraft [3]. The low landing speeds of V/STOL aircraft allow more time for pilot decision making and maneuvering, which may be favorable during instrument conditions [4, 3].

1.1.2 Lunar Lander Requirements

The need for precision landing on the Moon or Mars is driven by the uncertainty in the terrain, as well as the requirement to be able to land near another vehicle or infrastructure, or be able to reach specific locations of interest from the landing site. In support of the United States' vision to return humans to the Moon and Mars by 2012 for novel exploration, the next generation Lunar lander must be capable of achieving pinpoint, anytime, anywhere safe landing on the Lunar surface with high precision (10-100m) [1]. Current work towards this goal indicates that a vertical landing, similar to that of Apollo, will most likely be used for landing humans and equipment on the surface. While the Apollo trajectory included a vertical descent from roughly 50 feet, which allowed the crew to preview the landing site upon approach and then descend on to it, the proposed trajectory for returning to the Moon may include a more distinct vertical descent. This is to allow sensors to conduct hazard detection and avoidance during the vertical descent, and create a synthetic view of the landing site for the crew [1]. Figure 1-1, not drawn to scale, illustrates the comparison between the Apollo landing trajectory and a proposed return trajectory. The requirement for a vertical landing motivates the need for improved landing aids over those that did exist for the Apollo Lunar landings.



(a) Apollo Landing Trajectory (b) Future Moon Trajectory (adapted from [1])

Figure 1-1: Moon Landing Trajectories

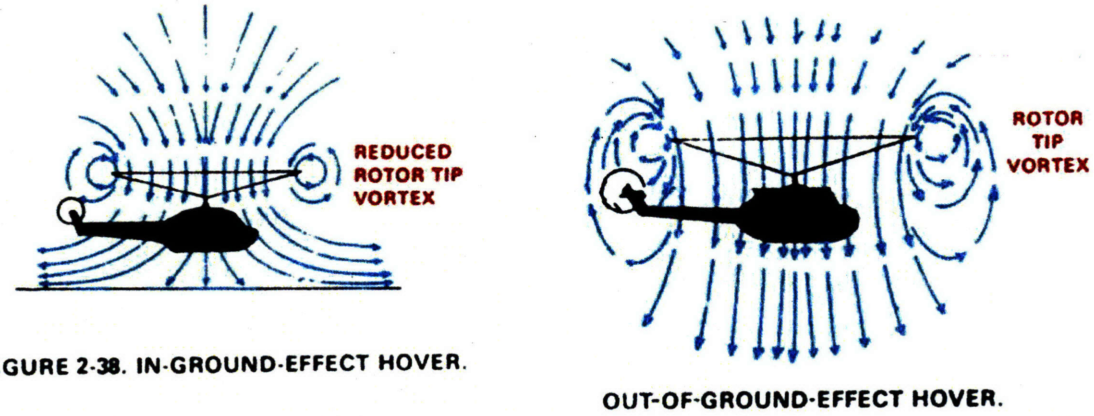
1.1.3 Vertical Flight Challenges

Numerous challenges accompany the ability to conduct safe vertical operations in air and spacecraft. An understanding of these challenges will provide an appreciation for the periods of flight during which precision and safety is most applicable, when instruments and displays are most utilized, and why a perceptual precision landing aid is needed by pilots of vertical air and spacecraft.

Ground Effect

One challenge that pilots face is ground effect, which is created when the ground interrupts the flow of air around part of a vehicle [5]. For helicopters, ground effect is generally a positive effect that improves performance when the aircraft is near the ground (within about 1/2 of the rotor diameter) because of the reduced velocity of downward airflow and the reduction in rotor tip vortex [6]. Since the airflow is interrupted by the ground, its velocity is reduced when flowing back down through the rotor disk. This allows the lift to increase and thus improves performance. Essentially it creates extra lift which means the helicopter requires less power to hover in-ground-effect (IGE).

When a helicopter is farther from the ground, the circulation of air through the rotor disk and back around can cause turbulence and instability if the vortex swirls are too large. Therefore, out-of-ground-effect (OGE) hovers require more power and are often more unstable making it a difficult, though sometimes neccessary, task. Because of this instability, helicopter pilots report that they are more concerned with their instruments and vehicle state during this phase of flight. Figure 1-2 illustrates the difference between in and out-of ground effect.



(a) In-Ground Effect

(b) Out-of-Ground Effect

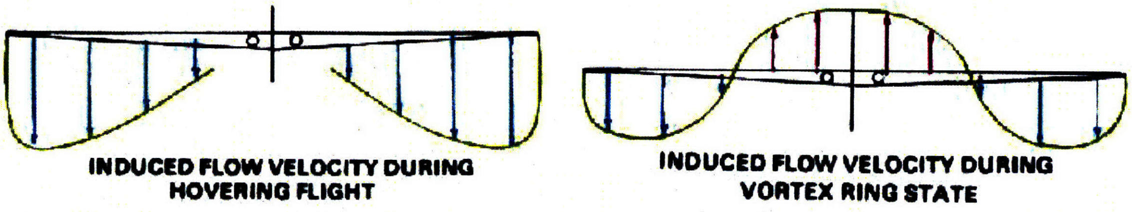
Figure 1-2: Ground Effect(from [6])

On the other hand, IGE can be unfavorable for some V/STOL aircraft, depending on the configuration, because it sometimes causes a suction effect that pulls the aircraft to the ground [3]. Jet-lift V/STOL aircraft, such as the harrier, sometimes experience this effect. In a study conducted using the NASA Ames V/STOL Systems Research Aircraft (VSRA), which is similar to a Harrier, pilots were asked fly a decelerating approach to a hover followed by a vertical landing. Afterwards they were asked to rate the handling qualities for a vertical landing. While the ratings were adequate, the pilots noted that they considered the principal deficiency of ease of landing to be "the considerable attention and compensation required to control sink rate during the descent in the presence of ground effect" [7, p.48] - a stark contract from the experiences of helicopter pilots IGE.

Vortex Ring States

Another challenge is vortex ring state (VRS), which is applicable to rotorcraft such as helicopters and the V-22 Osprey. Entering a vortex ring state is often referred to as "settling with power" and occurs when the rotorcraft descends into its own vortices, or downwash, disrupting the flow that creates lift. The VRS can be initiated by descending too quickly (generally > 300 fpm) while applying power and traveling at low airspeeds (typically considered < 30 knots) [8]. Entering a vortex ring state causes a loss of control and of stability, which is irrecoverable in extreme cases. For this reason, rotorcraft pilots are especially concerned with their descent rate during a powered vertical landing and depend on their instruments in addition to their visual cues to determine this.

Numerous helicopter and Osprey mishaps have been attributed to VRS. In April 2000, a simulated non-combat evacuation mission including four MV-22 Ospreys from the Marine Aviation Weapons and Tactics Squadron One (MAWTS-1) ended in a mishap of one of the Ospreys and the loss of all 15 Marines and 4 crew members aboard due to a VRS situation as a result of a descent rate exceeding the flight envelope [8]. Figure 1-3 illustrates the airflow through rotor blades for normal hover operations versus those experiencing a VRS. As illustrated, in the VRS the induced flow is upward through the inner portions of the blades thus reducing lift.



(a) Hovering Flight

(b) Vortex Ring State

Figure 1-3: Vortex Ring States (from [9])

In some cases it may be impossible to recover from a VRS, especially if the aircraft does not have the necessary altitude. In a helicopter, a pilot can try to recover from a VRS by lowering the power, pitching the nose down and attempting to gain some forward velocity. Similarly, the Osprey can recover by rotating the nacelles (the double rotor blades) to a more horizontal position in order to gain forward velocity. In both cases, once airspeed has increased, an increase in power is necessary to cease the fast descent rate [8].

Meteorological Flying Conditions

While flying in adverse weather conditions is never desirable, it is sometimes neccessary. In the aviation domain, weather drives the procedures, which are defined as meteorological flying conditions. The procedures are primarily a function of visibility or how far ahead the pilot can see. Visual meteorological conditions (VMC) enable visual flight rules (VFR) to be used if there is a clear visual of the natural horizon and the ground that can be used as a reference [10]. Pilots still use their instruments as references during VFR flight, but the outside world provides the primary attitude and rate cues.

Instrument meteorological conditions (IMC) are those conditions in which instrument flight rules (IFR) are required. IFR is flight with reference to the instruments only and is neccessary when weather causes low ceilings and visibility [10]. A ceiling is an overcast layer that precludes a pilot from traveling through it under VFR. Fog, haze and smoke, dust and sand, and precipitation can cause IMC [10]. Helicopter and V/STOL aircraft pilots rely strongly on their outside visual cues to determine a change in position and compensate for that change through control inputs [11], so a loss in visual cues requires that instruments be designed in such a way as to provide similar information in an intuitive manner. As of now, however, only high-workload tools are in place to aid pilots with hovering without those visual cues. Flying under instrument conditions is necessary to be able to exploit the full operational advantages of helicopters and V/STOL aircraft, such as operating from remote sites and landing in confined areas [4]. Once instrument rated, Harrier pilots can fly in weather down to 200 feet ceilings and one-half mile of visibility using IFR.

Nighttime flying can be done using VFR or IFR, however it presents several unique challenges. When using VFR, visual illusions affecting the determination of height, distance, and identification of stars or lights in the distance can severely influence the pilot's situation awareness. According to a mishap survey for the U.S. Army published in 1999, 31% of all U.S. Army rotary-wing mishaps between 1987-1995 were due to spatial disorientation [12]. Most of these mishaps were caused by unrecognized spatial disorientation and occurred at night, when visual cues are not as prominent. Unfortunately visual and vestibular cues do not always provide accurate information, making flight instruments and displays critical tools during nighttime flying.

Visual Disruptions

Closely related to meteorological flying conditions is the issue of brownout or whiteout conditions. Brownouts (also known as dustouts) and whiteouts are the result of the air movement caused by the rotors or jet exhaust close to the ground which can create a cloud of sand or snow which significantly reduces visibility during the final portions of a vertical descent [8]. An example of brownout conditions is illustrated in Figure 1-4. In the United States' current major engagement, Operation Iraqi Freedom, multiple aircraft and lives have been lost due to failed landings in dustouts [13, 14]. Dustout conditions create a similar problem as night or IMC flying, which can be alleviated to some degree through the use of instruments and flight displays.

Figure 1-4: Brownout Conditions (from [15])

Dustouts also posed a problem during the Apollo Lunar landings. While all of the Apollo landings experienced some dust, some landings were more obscured than others. The Apollo 15 landing was one of the worst dustout conditions that the astronauts encountered. Mission commander Dave Scott described the dust during the landing when he stated that "At about 50 to 60 feet, the total view outside was obscured by dust. It was completely IFR. I came into the cockpit and flew with the instruments from there on down" [16, p.1]. The Lunar surface dust will remain a challenge for future missions to the Moon, as well as possible landings on Mars.

Mitigating These Challenges

Each of these challenges of vertical flight can affect the pilot's cognitive state by forcing the pilot to incur additional, mentally demanding processes to maintain control and stability of the aircraft or spacecraft. These processes require maintaining significant amounts of information in short-term memory stores and mentally relating and projecting disparate variables to gain a clear understanding of the current situation or state. As Figure 1-5 illustrates, the many challenges that pilots face can be overwhelming.

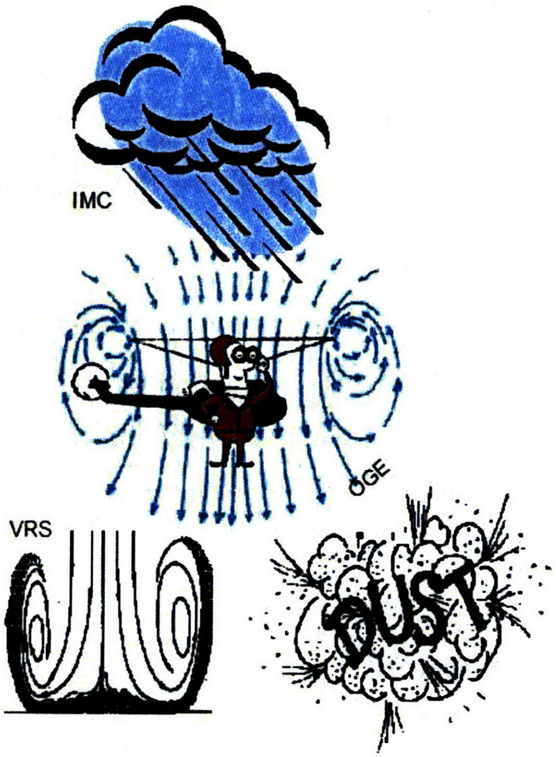


Figure 1-5: Vertical Flight Challenges

These challenges are primarily caused by a loss of sensory inputs, or a loss of stability that requires precision control to avoid or recover from these unsafe conditions. The loss of visual inputs and the need for precision control can both be addressed through the use of displays and individual display design. Each of these vertical flight challenges can be mitigated through display design in the following manner.

- *Ground Effect*: While the presence of or lack of ground effect presents different challenges for different V/STOL aircraft, the challenges all relate to the control of vertical speed at very specific altitudes. Therefore, the integration of these two sources of information on the display in such a way that both can be directly perceived and appropriately manipulated would help mitigate this challenge.

- *Vortex Ring State*: As vortex rings state or "settling with power" is caused by an excessive descent rate at low airspeeds while applying power, the display of this vertical speed limit that visually indicates the current position in relation to that limit may help mitigate this challenge.

- *Meteorological Flying Conditions*: Poor meteorological flying conditions that require instrument flight rules necessitate that critical information that is usually provided by outside visual cues, be displayed in an intuitive manner inside the cockpit.

- *Visual Disruptions*: Visual disruptions, which also temporarily eliminate many of the commonly used outside visual cues, require an intuitive display of critical flight information in a way that can be quickly referenced. This way, the display can be used in conjunction with the reduced visual cues to provide a clear understanding of the situation.

1.1.4 Problem Statement

The challenging conditions that accompany vertical flight, in particular the hovering and landing aspects of vertical flight, place high cognitive demands on pilots. Flight instrument displays are becoming increasingly important for mitigating these challenges as the demand for vertical aircraft increases, particularly in difficult operating conditions. The high cognitive demands of vertical flight, particularly in unfavorable operating conditions, demand intuitive and perception-based displays that present a large amount of information to the pilot quickly. A decision support tool which satisfies this need by taking advantage of direct-perception interaction [17, 18] through leveraging ecological perception and emergent features will be the focus of this research effort.

1.2 Research Objectives

In order to address the problem statement, the overarching goal of this research is to develop a decision support instrument for vertical landing. This goal will be addressed through the following research objectives:

- Objective 1. **Study the cognitive strategies employed by air and spacecraft pilots conducting vertical descents.** In order to achieve this objective, a cognitive task analysis was conducted and a cognitive model developed for vertical landing and hover operations, both of which are described in Chapter 3. Based on the data collected, the propagation of external and internal cognitive inputs through a pilot's or astronaut's cognitive processes and the mental steps required to achieve the goals of the mission were determined. The results of this analysis and model are outlined as design requirements for vertical landing instruments. A literature review on current vertical displays and the way in which they are used by the respective aircraft or spacecraft pilots was also conducted as part of this analysis.

- Objective 2. **Develop a vertical precision landing aid for use in aviation and space domains.** Based on the results of objective 1, an integrated flight instrument display component that addresses the design requirements outlined in Chapter 3 was designed (described in Chapter 4). A discussion of the design principles applicable to this display component and integration of this instrument into real-world flight systems is also included in Chapter 3.

- Objective 3. **Evaluate the effectiveness of the new vertical precision landing aid on hover and vertical landing performance.** To address this objective, human-participant experimentation of the proposed vertical precision landing aid was conducted. A description of the experiment is outlined in Chapter 5, while the results of the experiment and a discussion of their meaning are found in Chapters 6 and 7.

1.3 Thesis Organization

This thesis is organized into the following chapters:

- Chapter 1, *Introduction*, introduces and describes the motivation and research objectives of this thesis.

- Chapter 2, *Background*, provides a summary of the current technological state of air and spacecraft flight displays, discusses current vertical landing flight display research, and frames the context of the research objectives introduced in Chapter 1.

- Chapter 3, *Cognitive Processes for Vertical Landing and Hover Operations*, outlines the cognitive task analysis approach conducted for this research. A model of the cognitive strategies employed during vertical landings is introduced and described with respect to the cognitive task analysis results.

- Chapter 4, *Vertical Altitude and Velocity Indicator*, describes an integrated flight instrument display designed to aid with vertical landings, and introduces the design rationale.

- Chapter 5, *Human Participant Experimentation*, discusses the predicted performance of the Vertical Altitude and Velocity Indicator (VAVI). Details about the objectives, participants, and procedures utilized in the human participant experimentation of the VAVI are outlined.

- Chapter 6, *Results*, presents the statistical results of the experiment described in the *Human Participant Experimentation* chapter.

- Chapter 7, *Discussion*, compares the results of the human participant experiment with the hypotheses and discusses the applicability of the results to future integrated flight instrument display design.

- Chapter 8, *Conclusion*, summarizes the motivation and objectives of this research, how well the objectives were met, and the key contributions. Suggestions for future work are also provided.

Chapter 2

Background

This chapter presents a chronological summary of air and spacecraft displays that either currently exist or have existed to aid in vertical and/or precision operations for helicopters and V/STOL aircraft. First, displays used for Lunar descent will be discussed. Then, displays currently used for aircraft will be described, followed by rotorcraft and V/STOL operations. Finally, a summary of related research on vertical descent displays will be presented.

2.1 Apollo Landing Display Systems

The Apollo Lunar Module (LM) human-system interface is characteristic of the 1960's era of flight deck design. The LM cockpit consisted primarily of mechanical instruments such as pressure gauges, gyros, and switches as depicted in Figure 2-1. Since the United States has not landed humans on the Moon or other planets since 1972, these Apollo-era spacecraft cockpit displays remain the most current Lunar landing technology.

The lack of cathode ray tube (CRT) or liquid crystal displays (LCD) resulted in segregated information. The lack of automation and advanced glass cockpit technology that exists today, left the mentally demanding tasks of integrating information and drawing conclusions about the vehicle state up to the crew. Few instruments and tools directly supported the crew in their critical monitoring and commanding tasks.

The vertical descent portion of the Lunar landing was a particularly cognitively demanding task, jeopardizing the accuracy and safety of a landing. The few vertical landing aids to help minimize the cognitive demand are discussed in the following section.

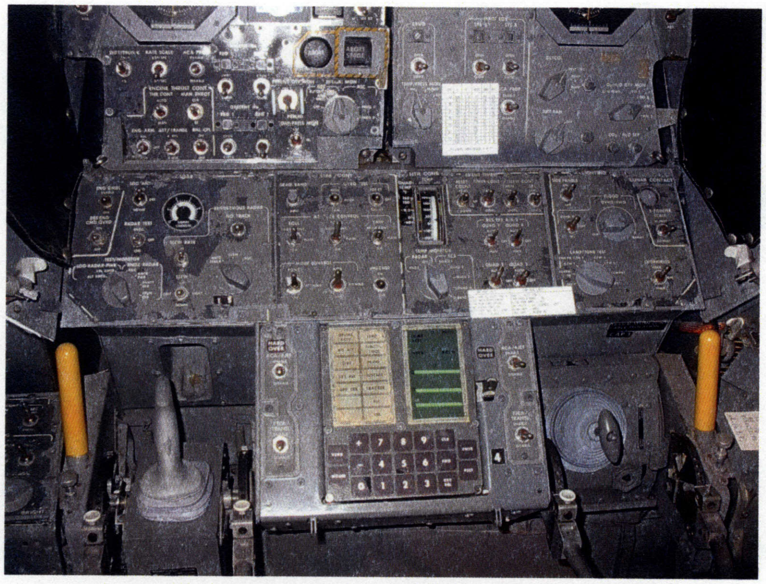
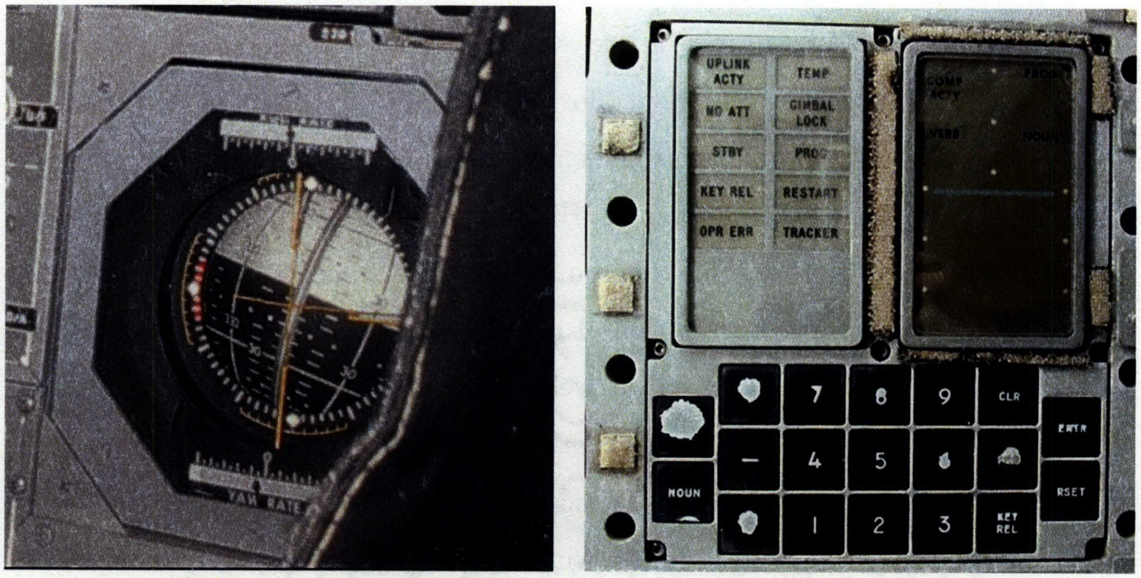


Figure 2-1: Apollo Lunar Module Cockpit (from [19])

2.1.1 Apollo Vertical Landing Aids

During the vertical descent portion of the Apollo Lunar landings, attitude, altitude, and sink rate information as well as any translational rates were the most critical pieces of information. The instruments used to monitor these key parameters, though physically located close together, were separate instruments that had to be scanned and cognitively integrated together by the crew to paint a complete picture of the current state of the vehicle and the landing. Altitude and sink rate (called altitude rate) were simple tape meter instruments co-located below the translational information and adjacent to the flight director attitude indicator (FDAI) (referred to as the "8-ball") illustrated in Figure 2-2a. In addition, the data storage and keyboard (DSKY) illustrated in Figure 2-2b was the display that enabled the crew to communicate with the Apollo guidance computer and was therefore also an important informational tool. Through the use of "noun" and "verb" commands, astronauts could get rate, direction, and time information and give commands to the guidance computer. For example, the mission commander typed in "Verb 50, Noun 18" during a Lunar landing to tell the computer to maneuver to the proper altitude for powered descent initiation [16].



(a) Flight Director Attitude Indicator ("8-Ball") (b) Data Storage and Keyboard

Figure 2-2: Apollo Lunar Module Cockpit Instruments(from [19])

2.2 Aircraft Display Systems

From the time of the Wright brothers and no display systems to the electro-optical instruments used today, advances in aircraft display systems have been tremendous over the last century. The majority of those advances have taken place in the last three decades advancing from purely mechanical instruments to the electromechanical era of Apollo and on to the electro-optical instruments widely used today. Flight displays are a critical air or spacecraft component because they provide necessary vehicle state information in the absence of visual cues or faulty vestibular feedback. The following section will be a short description of the most commonly employed electro-optical display system seen today in helicopters and V/STOL aircraft.

2.2.1 Head-Up Displays (HUD)

Head up displays (HUD) have been in existence since before 1970s, however it has only been in the last decade or so that HUDs elevated to the category of primary flight instruments [20]. The key attribute of a head up display is the collimated image of flight symbology or sensor video onto a piece of semi-reflecting glass such that important pieces of information are overlaid directly on the outside view of the world [20]. Though originally developed for weapons-aiming, the HUD has progressed into a widely used primary flight instrument [20], primarily in military aircraft where pilots are performing many tasks at once. HUDs eliminate the need for visual scanning and refocusing of the eyes from the electromechanical instruments in the cockpit to the outside view. Therefore the projection of HUD flight information further integrates data to include outside information as well as flight instrument data. Specifically, the display of altitude, vertical speed, attitude, and heading are the most commonly monitored flight parameters during a vertical landing. HUDs are a particularly useful technology for vertical landings during which the outside visual cues are especially critical. Figure 2-3 illustrates an example of a head up display.

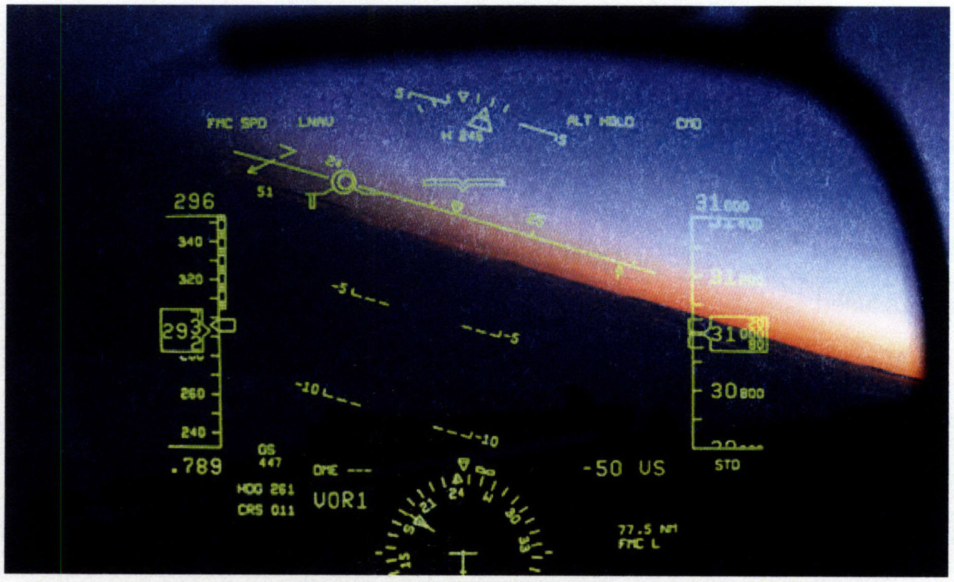


Figure 2-3: Head-Up Display (from [21])

2.3 Vertical Aircraft Landing Aids

Numerous examples of vertical landing flight displays exist today, each with slight aesthetic differences, but similar key pieces of information. Currently employed flight displays in helicopters and V/STOL aircraft present critical flight information as disparate elements within the display. In this section, examples of cockpit display elements that relate to altitude, vertical speed, and attitude for the following aircraft will be introduced and briefly described. These aircraft were chosen demonstrate a cross-section of helicopters and V/STOL aircraft.

- UH-60 Black Hawk, US Army (Figure 2-4a)
- AV-8B Harrier, US Marine Corps (Figure 2-4b)
- MV-22 Osprey, US Marine Corps (Figure 2-4c)

2.3.1 UH-60 Vertical Descent and Hover Displays

The UH-60 Black Hawk (Figure 2-4a) is a front-line utility helicopter used by the US Army for air assault, air calvary, and aeromedical evacuation. It has a 53-foot rotor diameter and can carry 11 combat-loaded troops [22].

The details of the UH-60 HUD are depicted in Figure 2-5. The key pieces of information which relate to fundamental vertical landing information are outlined in Table 2.1 and corresponds to the numbers in Figure 2-5.

Table 2.1: UH-60 HUD Description

Number	Definition
7	Barometric Altitude (MSL)
10	Velocity Vector
11	Rate of Climb Pointer
12	Radar Altitude (AGL) - Numeric
13	Minimum Altitude Warning
14	Radar Altitude (AGL) - Analog Bar
15	AGL, Vertical Speed Scale

(a) UH-60 Black Hawk (b) AV-8B Harrier

(c) MV-22 Osprey

Figure 2-4: V/STOL Aircraft and Helicopters

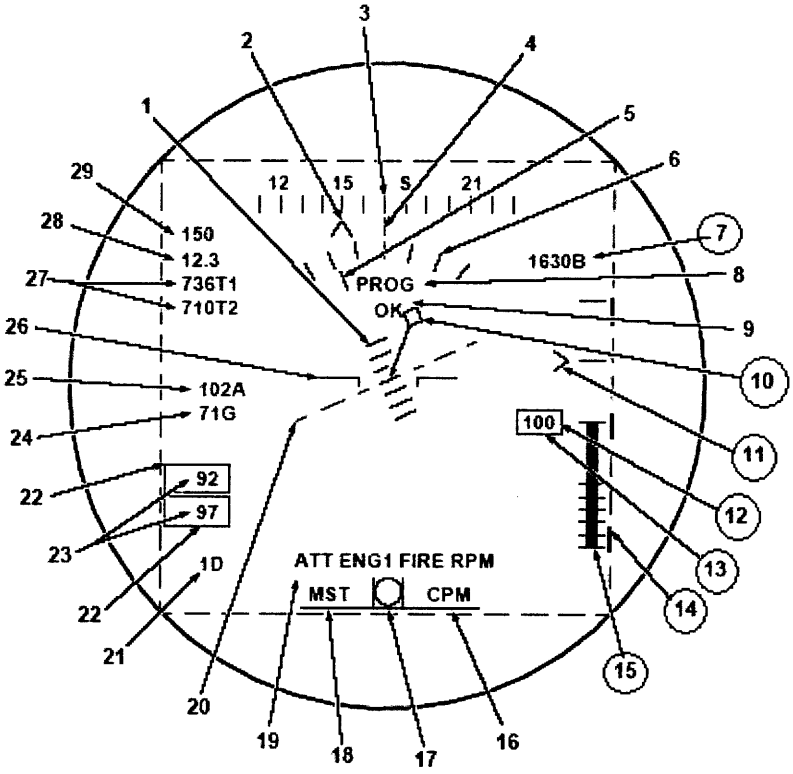


Figure 2-5: UH-60 Black Hawk HUD (from [23])

In this HUD, radar altitude[1] and vertical speed are depicted along the same analog scale, while the current radar altitude is also displayed digitally (up to 1000 feet). The radar altitude analog bar is depicted for 0-250 feet. It disappears at altitudes greater than 250 feet and reappears at 230 feet. Barometric altitude[2] is displayed digitally in the upper right corner of the display. Likewise, the vertical speed scale will indicate vertical speeds up to +/- 2000 feet-per-minute for altitudes up to 200 feet.

The velocity vector is applicable for 0-15 knots at which point it disappears for high speeds. Like many HUDs, the pilot can customize the display to include some or all of the display elements. In an interview with a Black Hawk pilot, he reported that he never includes the analog altitude and vertical speed scale in his customization of the HUD because he felt that it cluttered the display. This indicates that he does not find the information to be useful in his tasks, even at night when using night vision goggles (NVG) at which time visual cues are less prominent.

2.3.2 Harrier Vertical Descent and Hover Displays

The AV-8B Harrier is a jet-lift V/STOL aircraft that uses vectored-thrust to perform V/STOL operations at low speeds. The jet exhaust of the engine is directed downward using rotating nozzles which allows the aircraft to counter gravity. The Harrier is used by the US Marine Corps for close air support, anti-air warfare, and reconnaissance. It is capable of operating from carriers and remote tactical sites [22].

The Harrier V/STOL mode HUD is illustrated in Figure 2-6 which outlines key features of the display.

In the Harrier display, vertical speed and altitude are depicted separately. In the internal cockpit display (not shown), each parameter has its own analog scale along which the current value is indicated, either digitally or by way of a marker. In the HUD, altitude is only a digital readout while vertical speed is both a digital and

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[1] radar altitude is altitude determined by a radar-type altimeter and is the actual distance from the nearest terrain feature directly below the aircraft

[2] barometric altitude is altitude determined by pressure level and calculated according to standard atmosphere laws

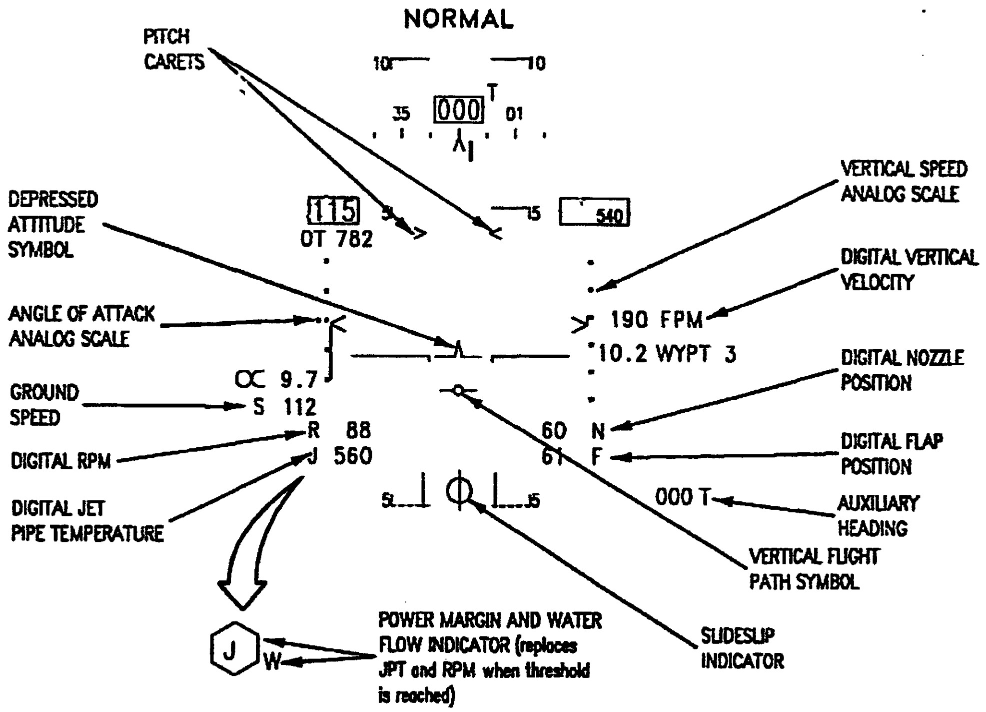


Figure 2-6: Harrier HUD (from [24])

analog depiction.

The Harrier HUD also includes two unique tools both for normal flight and vertical landings that are specific to the Harrier's configuration. First, the depressed attitude symbol outlined in Figure 2-6 is fixed 8 degrees below the waterline, which represents an imaginary line going through the middle of the aircraft in the vertical axis. Therefore, when the depressed aircraft symbol is on the horizon, the Harrier has a slight nose-up landing attitude. This is critical for a soft landing of the Harrier because it is designed such that on level ground, the nose is situated higher than the tail. This tool eliminates the need to compensate for the natural irregular Harrier attitude. Second, the position of the vertical flight path symbol (also called the velocity vector) gives vertical speed information. If the symbol is located above the horizon, it indicates that the vehicle is climbing, while a symbol below the horizon indicates a descent. At less than about 60 knots airspeed, this symbol matches the vertical rate. Therefore, if the depressed attitude symbol is on the horizon, and the vertical flight path symbol is 3 degrees below, then the vehicle is descending at 300 feet per minute.

2.3.3 Osprey Vertical Descent and Hover Displays

The V-22 Osprey is a tilt-rotor aircraft designed for use by US Special Operations Forces. The Osprey is capable of landing like a helicopter and then transitioning the engine nacelles to fly like a turboprop airplane at high altitudes and speeds. It's capable of carrying 24 combat troops or 20,000 pounds of cargo for use in amphibious assault, combat support, transport, and search and rescue operations [22].

The Osprey head down hover display and HUD are illustrated in Figures 2-7 and 2-8 along with Tables 2.2 and 2.3 that outline key features of both displays respectively. Figure 2-8a illustrates the HUD for hover mode and Figure 2-8b highlights key features of the HUD hover display.

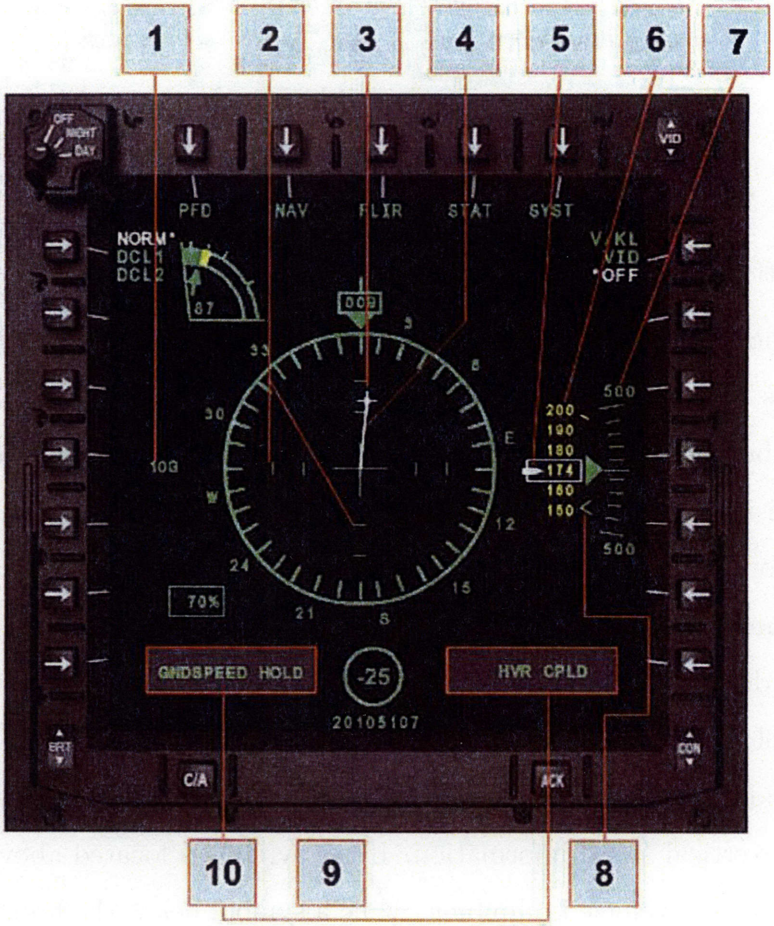
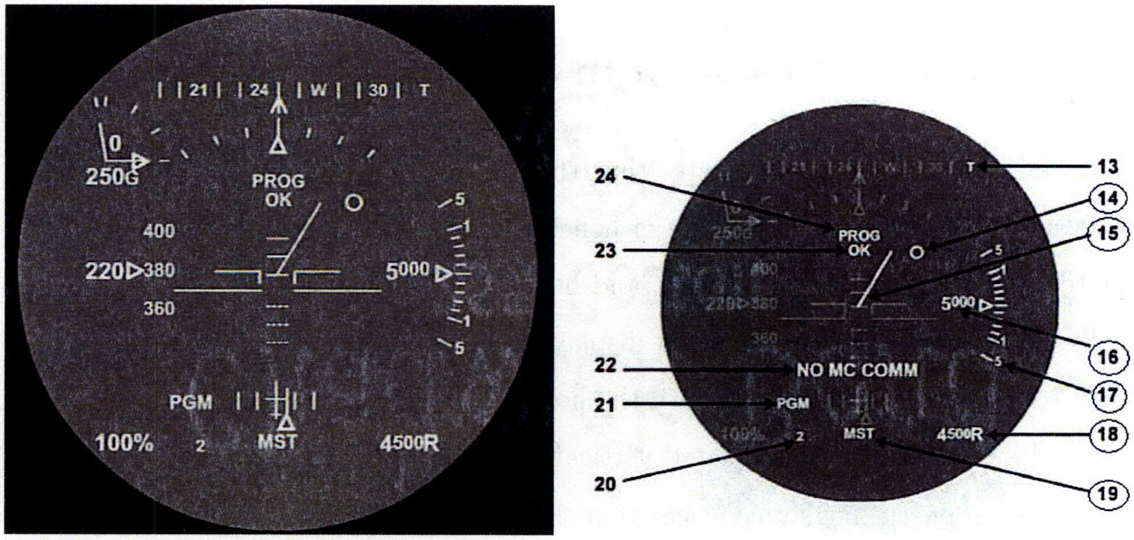


Figure 2-7: V-22 Osprey Display (from [25])

The display of altitude and vertical speed on both displays remains consistent or

Table 2.2: V-22 Osprey HDD Description

Number	Definition
1	Groundspeed
2	Velocity Vector Scale
3	Acceleration Cue
4	Velocity Vector
5	Commanded Radar Altitude Pointer
6	Radar Altitude (AGL)
7	Vertical Speed Range
8	Radar Altitude Low Set Pointer



(a)

(b)

Figure 2-8: MV-22 Osprey Hover Mode HUD (from [25])

Table 2.3: V-22 Osprey HUD Description

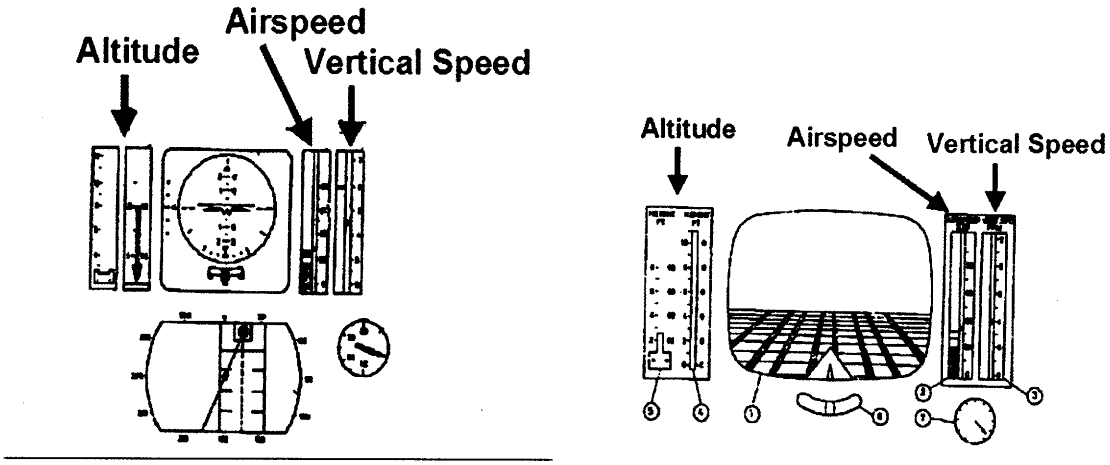
Number	Definition
14	Acceleration Cue
15	Velocity Vector (Hover)
16	Digital Barometric Altimeter
17	Vertical Velocity
18	Digital Radar Altimeter
19	Master Alert

at least similar to other rotorcraft or V/STOL aircraft. However, in this HUD, the digital altitude is located just to the left of the vertical velocity scale. This was done in an attempt to place the two pieces of information close together in such a way that the pilot can more clearly decipher and combine the two pieces of information to help gain a clear understanding of the vehicle state. However, the digital altitude that is displayed close to the vertical speed scale is barometric altitude and not a radar altitude. Radar altitude, which is displayed in the lower right corner, would be the more useful altitude at the low altitudes at which hover and landing operations take place.

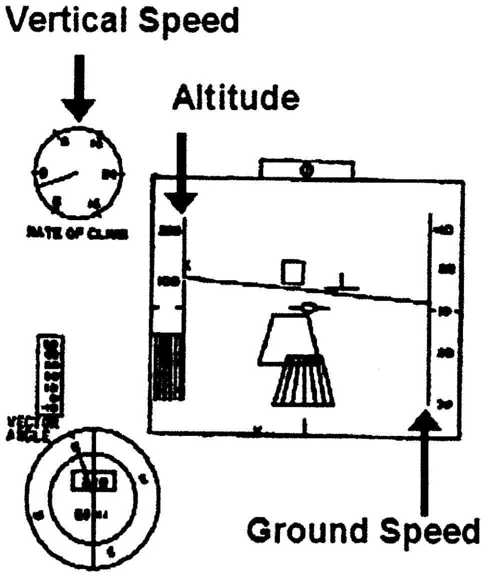
2.4 Related Research in Vertical Displays

A review of the literature indicates that the majority of related research on display concepts for approach and landing of helicopters or V/STOL aircraft does not adequately address the vertical descent and hover tasks in the vertical situation specifically. While many of the proposed display designs incorporate creative and unique ways to present information in both the horizontal and vertical planes, the majority of the designs display disassociated vertical speed and altitude information.

Three proposed display concepts that did not become operational are illustrated in Figure 2-9. Figure 2-9a and b illustrate two proposed designs that present the necessary vertical situation information not only as disassociated information, but on opposite sides of the primary center display. Altitude, vertical speed, and airspeed are all displayed as fixed scales with moving pointers. Figure 2-9c also illustrates a proposed V/STOL display which includes disparate information in two different analog forms. In this display, to address the vertical situation, altitude and ground speed are displayed along the left and right sides respectively as fixed analog scales somewhat combined with the center display. Vertical speed, however, is displayed to the left as a totally disjointed instrument. For all three displays, this critical approach and landing information is presented as raw data that that must be extracted and comprehended in relation to the pilot's specific tasks and goals. Therefore, these



(a) (from [4]) (b) (from [4])



(c) (from [26])

Figure 2-9: Proposed V/STOL Displays

displays provide no integration of the vertical situation parameters such as altitude and vertical speed for direct perception of the relevant meaning of the values. In this way, neither of these proposed displays specifically provides decision support for the vertical descent portion of flight.

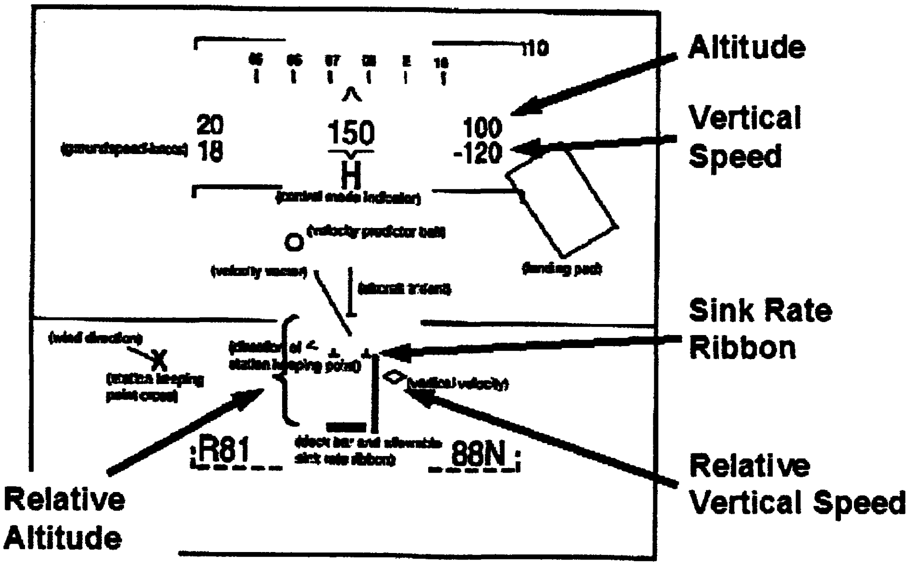


Figure 2-10: Display for Precision Hover (from [27])

One of a series of displays developed and tested using the NASA Ames V/STOL System Research Aircraft [27, 7, 28] illustrated in Figure 2-10 does attempt to integrate the vertical situation information. In this display, commanded vertical velocity is depicted by the diamond located along the allowable sink rate ribbon. The sink rate ribbon indicates the allowable range of sink rate which will ensure a safe descent, but does not visually map directly to any vertical speed values. Therefore it only provides a relative vertical velocity indication, while the exact vertical speed that corresponds to the diamond is displayed digitally at the top of the display. Similarly, a relative altitude indication is visually displayed as the distance between the "deck bar" and aircraft symbol, however the only exact information is displayed in the upper left corner.

While the display of allowable sink rate limits in Figure 2-10 is very useful to the pilot, the physical separation of this relative information and the exact value requires the pilot to move his/her gaze in order to get the full suite of information corresponding to vertical speed. The same is true for altitude which introduces an extra step by requiring the pilot to mentally store information from one part of the display while gazing at another part of the display. This is especially cumbersome during high workload descents during which altitude and vertical speed information is critical. In addition, by placing the digital vertical speed and altitude values right on top of each other in the upper right corner, the pilot must not only search for that general area of the display, but also search between those numbers for the number of interest, making it error-prone and slow. Numerous other display concepts took the same approach of physically separating relative and exact representations of vertical situation information (see references [4, 2] for more examples).

Another disadvantage of the displays illustrated in Figures 2-9 and 2-10 is the lack of goal-relevant vehicle state information that can be quickly assimilated with a single glance. For the display in Figure 2-10 this is attributed to the interactive nature of the display. This display requires the pilot to "move the velocity predictor ball to the landing pad and then follow the pad as it approaches and converges on the aircraft reference symbol" [27, p.166]. As mentioned in Chapter 1, most helicopter and V/STOL pilots are extremely dependent on their visual inputs when flying, especially during vertical operations. Therefore, only in the total absence of *all* outside visual cues (which would require an extreme situation), would a pilot be willing to totally remove his/her visual attention from the outside world long enough to focus on, comprehend, and control multiple symbols within a display in order to control his/her aircraft. Displays such as those in Figures 2-9 and 2-10, require too much information to be perceived and comprehended too quickly to be useful during a stressful vertical landing.

Chapter 3

Cognitive Processes for Vertical Landing and Hover Operations

This chapter provides an analysis of the cognitive strategies employed by air and spacecraft pilots during vertical landings. It then summarizes the design requirements that were revealed through the analysis for use in the design of future displays or flight symbology.

3.1 Cognitive Task Analysis

A cognitive task analysis was performed to gain a better understanding of air and spacecraft pilots' cognitive processes, key challenges, and what flight parameters are most crucial during a vertical landing. A cognitive task analysis, as defined by Chipman, Schraagen, and Shalin is "the extension of traditional task analysis techniques to yield information about the knowledge, thought processes, and goal structures that underlie observable task performance" [29, p.3]. The cognitive task analysis used in this thesis corresponds to this definition and included the following techniques:

- *Semi-Structured Interviews*: Interviews were conducted with various helicopter, Harrier, and Osprey pilots, Apollo engineers and ground controller personnel, and the following Apollo astronauts: Buzz Aldrin, John Young, and Harrison Schmitt. Open-ended questions were used to guide the interviews. Interviews were either conducted in person or over the telephone and each interview lasted approximately 45 minutes to 1 hour.

- *Simulator Experience*: An AV-8B Harrier pilot located at Cherry Point Marine Air Station in Cherry Point NC provided simulator demonstrations and the opportunity to fly the simulator. A V-22 Osprey flight instructor at New River Marine Air Station in Jacksonville, NC provided a two hour tour of the six degree of freedom Osprey simulator.
- *Transcript Analysis*: Analysis of the Apollo Lunar Surface Journal was conducted to better understand, through the astronaut's communications, how a vertical landing on the Moon was conducted.
- *Storyboards and Timelines*: A compilation of the transcript analysis and other resources were used to create a storyboard and timeline of the Apollo Lunar landing which highlighted key tasks and periods of high workload.

3.2 A Cognitive Model for Vertical Landing

Endsley's model of situation awareness (SA) was modified to illustrate the cognitive processes that are required for achieving SA for pilots or astronauts performing vertical landings or hover operations [30]. This model, illustrated in Figure 3-1, captures the key elements of SA as well as the external information and information stored in memory necessary for developing SA during vertical landings. Everything contained within the gray box represents the cognitive processes of a pilot or astronaut, while everything outside of that box represents the external world. Situation awareness, as defined by Endsley, is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [30, p.36]. Situation awareness flows directly into decision-making and action implementation at which point the effects are perceived through the feedback and SA is reconstructed and reevaluated. This cascading sequence requires high situation awareness for making a good decision and corresponding action. Each level of SA and the surrounding cognitive processes for managing altitude and vertical speed during a vertical landing are described in more detail in the following subsections.

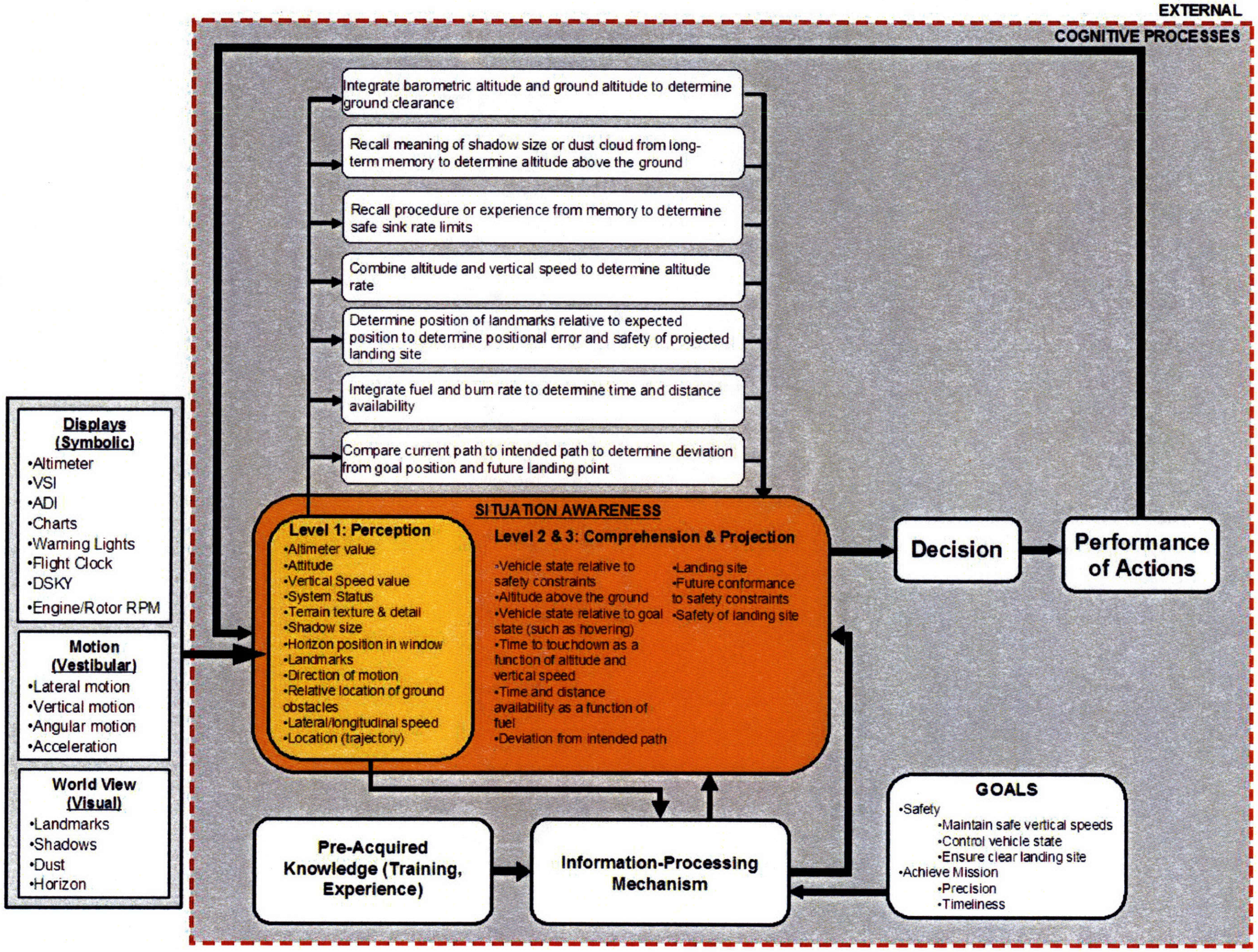


Figure 3-1: Cognitive model for managing altitude and vertical speed during a vertical landing (adapted from [30])

3.2.1 External Inputs

The external inputs highlighted in the model emphasize the primary sources of information the pilots rely on to determine their current position in relation to their goals [31]. The three input sources include:

- *Visual*: information provided by the outside view of the world.
- *Vestibular System*: information provided by changes in gravitational forces on the body.
- *Symbolic*: information provided by flight instruments and displays within the cockpit.

The visual inputs specific to vertical operations include such things as geographic and man-made landmarks, shadows, dust, and the horizon. Although many helicopters and V/STOL aircraft are equipped with old navigational technology such as Lorans and VHF-Omnidirectional-Range (VOR) radio navigation, or newer technology such as GPS, some operations heavily utilize pilotage[1]. Similarly during all Apollo landings, predetermined landmarks were used to ensure the spacecraft was on the appropriate trajectory for landing. Landmarks also provide key peripheral and depth perception cues which indicate vehicle height. The familiarity with the objects in conjunction with the visual feedback they provide in terms of texture and detail provides a sense of vehicle position relative to the ground to ensure current and future ground clearance. Pilots and astronauts also use the placement of landmarks or the horizon within their windows to determine any lateral or longitudinal movement and descent rates for positioning during a stationary hover. A Harrier pilot described how he would situate the aircraft such that he had a landmark to the front and to the side of him in order to provide both vertical and horizontal relative movement information. Shadows (if the operation is conducted at the appropriate time) can also provide ground clearance information through their dynamic size during a descent,

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[1] Pilotage is navigation by visual reference to landmarks [32]

as can dust which indicates a certain proximity of the thrusters or rotor blades to the ground.

The pilot's vestibular system, located in the inner ear, responds to gravity to sense angular motion, accelerations, and position [33]. In vertical operations, this system is important for sensing lateral, vertical, and angular motion as well as any acceleration in those directions in order to maintain a hover or descent with minimal lateral or longitudinal motion. The vestibular system can also be misleading or unreliable. According to Young, visual information "frequently conflicts with motion or orientation signals emanating from the vestibular system" [33, p.83] and some experts argue that "pilots should ignore vestibular information all together to be safe in a low-altitude environment" [31, p.50].

The symbolic information, or the presentation of that information within the cockpit, is often unique to the vehicle platform. As outlined in Figure 3-1, an altimeter, vertical speed indicator (VSI), attitude direction indicator (ADI), and on-board charts and vehicle status warning lights are just a few of the flight instruments that provide symbolic information. Since visual and vestibular feedback can provide erroneous cues, the symbolic information displayed through these flight instruments is a critical input for achieving high situation awareness.

3.2.2 Internal Inputs

Situation awareness is also driven by internal cognitive inputs from long term or working memory. Any pre-acquired knowledge gained through training or experience is of key importance in the tasks in this model. This source of information is stored in long-term memory and flows directly into the information-processing mechanism. Long-term memory structures allow pilots to act appropriately based on scripts that form through repeated training and past experiences [30].

Working memory, not explicitly represented in the model, but is subsumed in the information-processing function, compliments the information-processing mechanism by filling the gap between the long term memory stores and the unique elements of the current environment in order to determine the appropriate action. This is where the majority of active processing takes place.

In addition to memory, the goals of the mission also drive the cognitive processes of the pilots. In the case of vertical precision landing and/or hover operations, the two foremost goals are safety and mission success within which several minor goals reside. Safety is dependent on many factors, however those that correspond directly to vertical landing and hovering include maintaining a safe attitude (i.e. staying within the pitch and bank constraints of the vehicle), safe descent rates, and an obstacle-free landing zone. Mission success for precision landing can be directly measured by the accuracy and safety of the operations and the timeliness, which can be critical in many space and military operations.

Preattentive processing, also not explicitly represented in the model, is one information processing mechanism that helps bridge the gap between the external inputs and SA. According to Endsley [30], certain object characteristics, such as spatial proximity, color, etc, are detected initially through the parallel processing of environmental features through preattentive sensory stores. These serve as the cues that drive further localized attention on the objects that are the most salient, to achieve perception. Therefore cue salience has a significant impact on which elements of the environment are attended to and subsequently perceived [30].

3.2.3 Perception

The first level of SA is perception of the "status, attributes, and dynamics of relevant elements in the environment" [30, p.36]. For pilots and astronauts, this information comes directly from the three primary external sources described in section 3.2.1. While some of the attributes can be directly perceived from the flight instruments (such as altitude, attitude, and vertical speed), other characteristics are perceived from the outside view (e.g. texture, detail, projection of light) and are then processed to gain additional information. These are the processes that facilitate the transition to comprehension and will be described in more detail in the next section. Information such as the relative location of ground obstacles is more easily perceived directly from the outside world. It is the parallel processing of these various sensory external inputs that creates the first level of situation awareness.

3.2.4 Comprehension and Projection

Comprehension of the current situation is the second level of situation awareness. At this level, the integration of level 1 information and the external goals creates an understanding of those perceived elements with respect to the relevant goals [30]. During comprehension the pilots compensate for missing or segregated information by relying on memory and information-processing to get them from the information they can directly perceive to the information they actually need to achieve their goals. The greater the mismatch in the information available and the information needed to achieve the goals, the higher the cognitive workload required to perform information-processing and recall from memory.

Some of the key goals of a Lunar or earth-based vertical landing are outlined in Figure 3-1 and feed directly into the information-processing mechanism. The first goal, safety, includes maintaining safe sink rates and control of the vehicle state, and ensuring a clear landing site and safe ground clearance. To maintain safe sink rates, the pilot or astronaut must perceive the current altitude and current vertical speed from a combination of individual symbolic displays, vestibular feedback, and visual stimulants. The perception of this information is important, but the comprehension of its meaning is arguably more critical. While the outside world and vestibular system can provide relative sensory feedback on altitude and vertical speed, the instruments within the cockpit provide more accurate and precise information especially in the absence of visual cues during the low visibility situations discussed in Chapter 1. Since current vertical speed indicators do not indicate sink rate constraints for safe descents, the comprehension of this information requires that the pilots or astronauts recall from memory the heuristic they were taught that guides the dynamic safety constraints relative to altitude. The practice of teaching safe descent heuristics is a common one that was uncovered through the cognitive task analysis. They either apply these heuristics or match the current situation to a past experience stored in memory and perform according to their knowledge of those results (according to the theory of naturalistic decision-making [34]). In interviews conducted with Harrier, Osprey, and helicopter pilots, they reported this error-prone and mentally taxing step, usually referring to their training as the primary source of information for comprehending the raw data with respect to the safe sink rate constraints. However, relying on memory for the heuristic does not provide a comprehension of the vehicle state relative to those constraints. Consequently an additional step is required, which involves comparing the dynamic sink rate (which may only involve perceiving a digital number on the display) to the known heuristic, while compensating for the rapidly changing value. This process is illustrated in Figure 3-2 and demonstrates the mentally taxing process associated with comprehending perceived raw data in a dynamic environment.

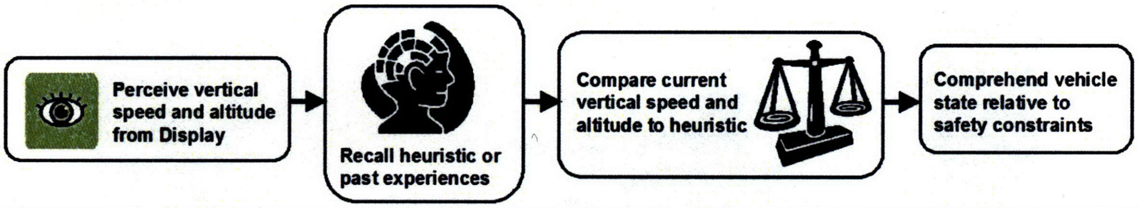


Figure 3-2: Progression from perception to comprehension of vehicle state relative to safety constraints

Pilots and astronauts are also concerned with vehicle state relative to the state in which they wish to be. Hovering is a good example of this situation. In order to hover at a precise altitude, pilots must focus on altitude, vertical speed, heading, and torque (for helicopters) or nozzle/rotor position and power (for Harriers and Ospreys), switching between them in order to achieve the desired state through the appropriate control inputs. The individual pieces of information may be directly perceived as values on the display, but the meaning of those values relative to the goal requires the mental integration of the two sources of information. Helicopter pilots reported that when visual cues are absent, this mental integration is overwhelming at times.

Ensuring a clear landing site and ground clearance during a descent primarily depends on the pilot's comprehension of altitude above the ground, taking into account any obstacles or hazards below. Shadows and dust provide visual cues of relative altitude which pilots utilize. Like sink rate, the direct perception of the size of the shadow is meaningless without pulling from long-term memory stores to comprehend the approximate altitude associated with that shadow size. While Harrier, Osprey, and helicopter pilots reported using the shadow occasionally as a cue, they did not specifically address the use of this cue in training. In contrast, Apollo astronauts trained to use the shadow as a relative altitude reference. Since the Moon landings happened at well-known and pre-planned times, the shadow size was predictable and could therefore be incorporated into training. Figure 3-3 illustrates the shadow of the Apollo 11 Lunar Module on descent. Both groups, however, must pull from experience and memory to comprehend the perceived shadow size as illustrated in Figure 3-1.

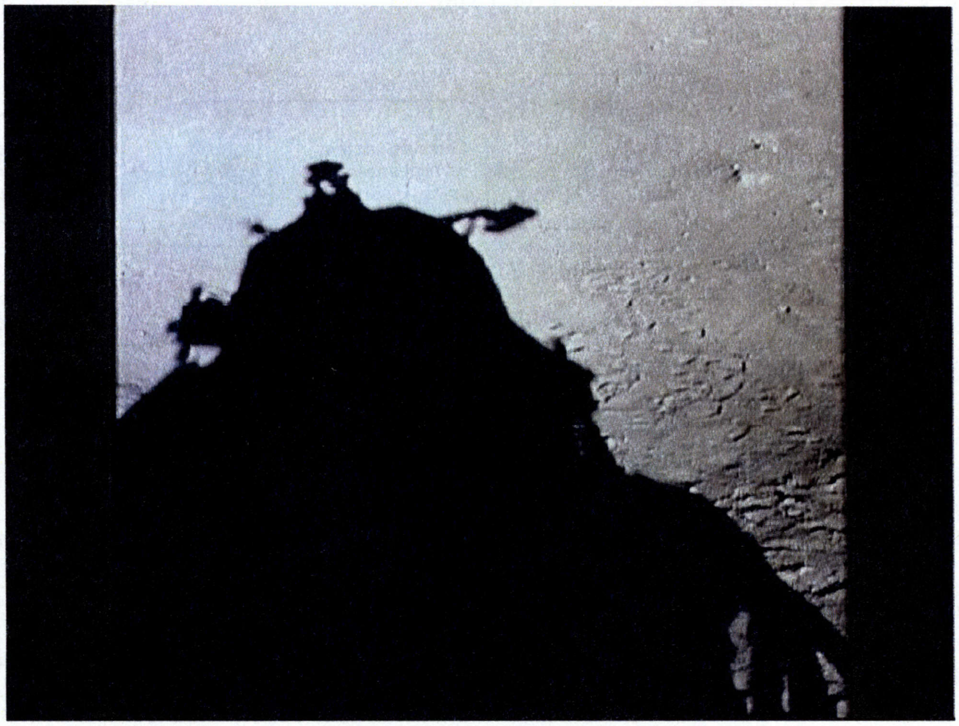


Figure 3-3: Apollo 11 Lunar Module Shadow

Pilots and astronauts also depend on the perception of values on their displays for altitude information. A digitally displayed value of altitude can be directly perceived, but to comprehend its meaning in terms of ground clearance is more difficult. Analog representations of altitude allow for a more direct perception of relative altitude and thus vehicle position as it relates to the goals. Several aircraft displays provide barometric altitude only (with knowledge of ground altitude) or display it as the primary altitude of interest with radar altitude displayed in a secondary location. Barometric altitude is often more accurately measurable and thus is the primary reason for predominantly displaying it. For vertical operations close to the ground, however, barometric altimeters are virtually useless. One barometric altimeter, the Stratomaster Maxi Single is only calibrated to ±30 ft, which at low altitudes is not very helpful [35]. Therefore, ground clearance or true height above the ground is of chief importance during vertical landings. In situations in which this critical information is not displayed such that it must be visually estimated, ground altitude and barometric altitude must be mentally integrated, creating a mentally taxing vertical landing.

To address the timeliness goal if landing in a narrow window of time is critical, as it was during the Apollo missions, comprehending the time to touchdown requires mentally integrating altitude and vertical speed (both highly transient) at any given moment in time. This extremely simple task for automation can be mentally demanding step for a human during the high stress period of a vertical descent.

The third and highest level of situation awareness is the projection of the comprehended information into the future. Projection is achieved when an understanding of the perceived attributes and the dynamics of the specific environment can be extended into an understanding of a future state relative to the goals [30]. For pilots and astronauts performing vertical landings, comprehension and projection are tightly coupled due to the highly dynamic nature of this phase of flight. Since the time constants are so short and part of understanding involves projecting into the future, these two steps are essentially concurrent. In other words, since it is a manual control task during which flight parameters are changing every second, the extent of the pilot's projection of vehicle state into the future is limited because it is happening almost concurrently with the comprehension.

Some of the information that the pilots are able to project further into the future, however, are the approximate touchdown point and the safety of that site. To determine the landing site, pilots and astronauts must combine rate and position information and project it into the future. Likewise, determining the safety of a projected landing site involves mentally comparing the perceived and comprehended relative position of obstacles and hazards, to the projected landing site in order assess the safety situation. In the model illustrated in Figure 3-1, these mental steps are highlighted from level 1 to levels 2 and 3 SA.

It is also important to note that several of the environmental cues that are often used, perceived, and propagated through each level of situation awareness are unreliable. For example, the use of familiar landmarks to determine location is a common perception-comprehension sequence used by pilots and the Apollo astronauts. A mismatch in the transition from perception of individual landmarks to their meaning about vehicle position took place during the Apollo 15 mission. Mission commander Dave Scott revealed that right after pitchover and upon his first view of the landing site, he was completely disoriented. As a result, he and astronaut James Irwin landed primarily using instrument flight rules (IFR). It was later determined that this confusion resulted from an exaggeration of the landscape in the Lunar surface model used for simulated landings [16]. Therefore the astronauts perceived the outside view, but were unable to comprehend positional information from it. As previously discussed, dust is another often unreliable cue which is highly dependent on external factors such as the surrounding environment. For example, sand will propagate through the environment much differently than dirt or snow. The perception of dust kicked up by thrusters or rotor blades can be associated with an altitude which corresponds to past experiences, but their unreliable nature could cause trouble if it is not correctly perceived. These two examples illustrate how an error in one level of situation awareness will propagate through the levels causing increased workload and an increased chance of serious errors.

3.3 Vertical Landing Display Requirements

The cognitive task analysis and adaptation of the cognitive processing model revealed that current vertical landing displays require a high cognitive workload and introduce room for error by requiring pilots to mentally integrate and perform calculations.

More specifically, a mismatch between the data provided by current instruments and the information needed by pilots to ensure a safe and precise landing became apparent through the cognitive processing model. Integrating these instruments to provide a salient display of the information required in a form that matches the mental model of the pilot and provides for direct-perception interaction, should significantly improve vertical landing operations. The design requirements identified and listed below for the design of future aircraft and spacecraft vertical landing and hover displays motivated the design of the proposed vertical precision landing aid introduced in the next chapter.

1. *Provide obvious display of sink rate safety constraints and a means for attaining pilot attention when the constraints are violated.* The display of maximum allowable rates of descent provides an indication of sink rate relative to the relevant goal of landing safely. Any lag associated with vertical speed measurement needs to be eliminated to provide reliable information [4].

2. *Enable direct perception of the combination of vehicle altitude and vertical speed to assist in quickly determining vehicle hover state.* The combination or integration of display parameters allows several parameters to be observed from one element [4] which addresses the difficulty in integrating dynamic vehicle parameters to gain position information.

3. *Display vehicle altitude above the ground as the primary displayed altitude during vertical operations.* This height, as opposed to the altitude above sea level, is of primary concern during a descent. An analog representation of altitude inherently provides a rough indication of the rate of change and specifically addresses the difficulty posed by a loss of visual cues for determining sink rate.

4. *Display the approximate time to touchdown.* The integration of vertical speed and altitude during a vertical descent should be done by the automation to remove this cognitively demanding step.

Chapter 4

Vertical Altitude and Velocity Indicator (VAVI)

This chapter presents the details of a precision landing aid called the vertical altitude and velocity indicator (VAVI) that was developed in response to the need for an improved display of altitude and vertical speed information with respect to system goals to support V/STOL aircraft or spacecraft pilots during a precision vertical descent task. Explanations of the proposed integrated flight instrument display functionality, appearance, and usage are outlined, and the rationale behind the VAVI's design is discussed.

4.1 Overview of VAVI

The VAVI was developed to address the challenges and design requirements that were revealed through the cognitive task analysis discussed in Chapter 3. The purpose of the VAVI is to help minimize the intermediary cognitive processes that are currently required to get from perception to comprehension and projection through the levels of situational awareness by directly conveying altitude and vertical velocity information to indicate unsafe situations and hover-maneuvers in an integrated form with obvious cues. It is intended to be used during hover and vertical descent operations.

The VAVI seeks to provide an intuitive integrated flight instrument display that leverages ecological perception and application of the emergent features and proximity compatibility principle. The VAVI consists of four major parts: altitude scale, vertical speed indicator, vertical speed needle and symmetric counterpart, and a clock. It is intended to be used in conjunction with other flight instrument displays. Figure 4-1 illustrates the details of the VAVI in context of whole display.

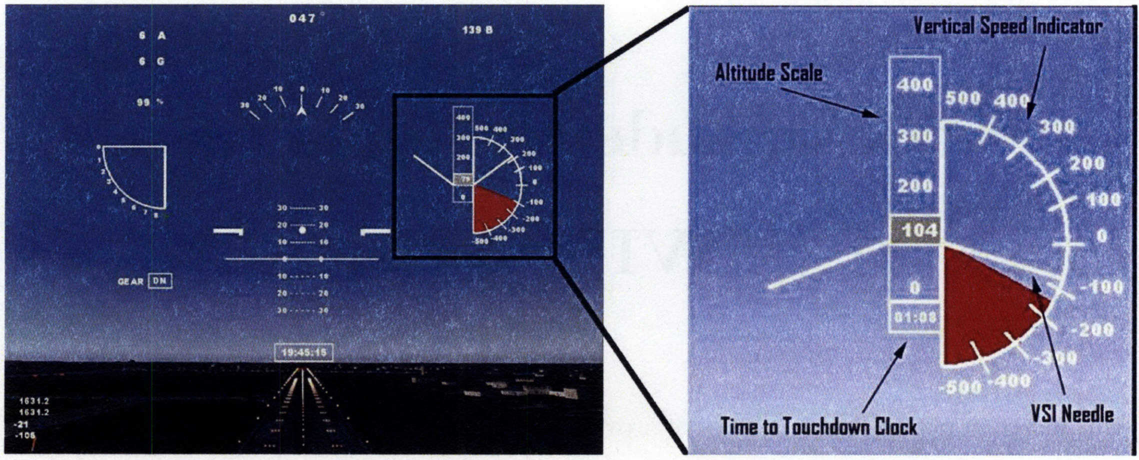


Figure 4-1: Vertical Altitude and Velocity Indicator (VAVI): Visit halab.mit.edu for videos of the VAVI

4.2 VAVI Integrated Flight Instrument Elements

This section describes the various elements of the VAVI. Their mapping to the design requirements in Chapter 3 is indicated where appropriate.

4.2.1 Altitude Scale

The center vertical shaft is a fixed altitude bar in units of feet. The range of the altitude is dependent on the altitude at which an air or spacecraft would initiate a vertical descent or hover. The VAVI shown here illustrates an example for application of hover and descent operations from 400 feet. This altitude was chosen for illustrative purposes. Altitude is both physically and conceptually analog in terms of quantity and representation. Therefore, the analog representation of altitude in the VAVI is most appropriate for conveying relative height information. Likewise the direction of increasing altitude on the altitude bar is consistent with the direction of physical movement.

The small gray box seen here at 97 feet, outlines the current altitude as a digital value that will slide up and down the analog altitude scale accordingly. This feature provides the altitude to a high precision while maintaining the analog representation of altitude. In this version of the VAVI, when the altitude exceeds 400 feet, the gray box will remain at the top of the fixed bar, while the digital value inside the box will continue to increase consistent with the current altitude above the ground.

4.2.2 Vertical Speed Indicator (VSI)

The half circle to the right of the altitude bar is the vertical velocity gauge in units of feet per minute (fpm) and depicts vertical speeds between ±500 fpm. The "arms" of the VAVI refer to the vertical speed needle (the right arm) and its symmetric counterpart (the left arm). The VSI moves as a unit vertically along the altitude bar such that the arms always protrude from the current altitude and the arm to the left of the altitude bar is symmetric with the right arm.

In conjunction with the altitude bar, the vertical speed indicator needle of the graphical display becomes a visually prominent element of the display that maps directly to the system states that are important to the operator. The position of the needle provides a cue as to what state the vehicle is in, including hover maneuvers and precision descents. Therefore the arms are cues that provide state information at a glance. A nominal ascent, descent, and a hover maneuver are illustrated in Figure 4-2a, b, and c respectively. Instead of mentally combining the altitude and vertical speed in an effortful approach to determine the vehicle state, the operation can now be carried out more automatically. The VSI in conjunction with the altitude bar to create the VAVI directly addresses design requirements 2 and 3 by providing a natural depiction of vehicle hover state and utilizing the radar altitude in close proximity to the vertical speed in order to combine the two most important pieces of goal-relevant information about the vehicle state.

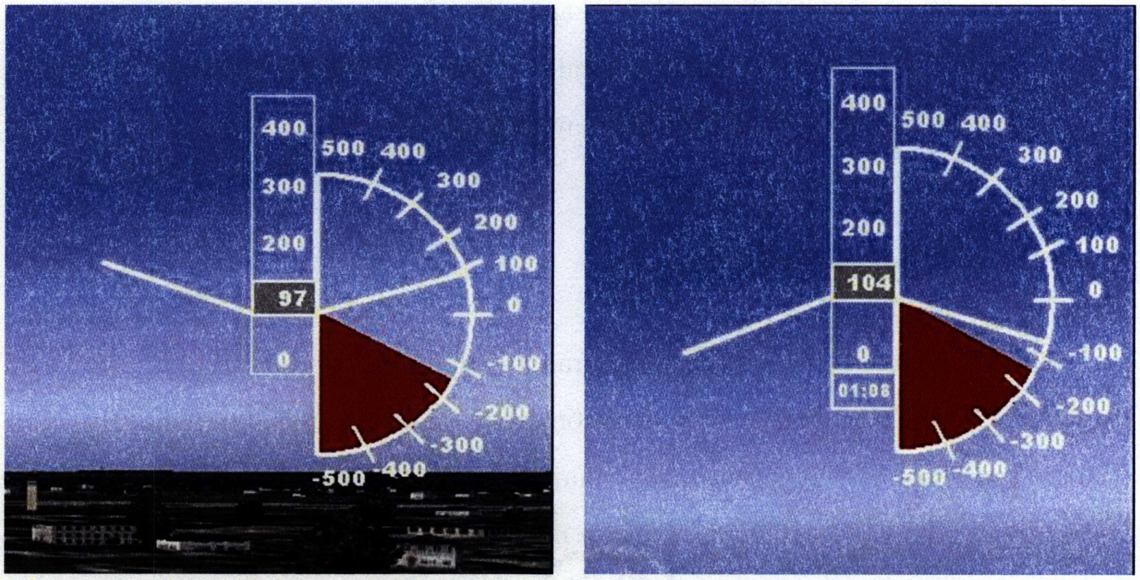
A key feature of the vertical speed indicator element of the VAVI is the inclusion of unsafe sink rate (negative vertical speed) zones. The red section of the gauge indicates an unsafe sink rate for the current altitude and vehicle and environmental conditions. When the vertical speed limit is violated the red zone becomes a brighter red, but could be indicated in a number for implementation in current displays. This design feature directly addresses design requirement 1 and is illustrated in Figure 4-2d. By including the dynamic unsafe zones, the pilot no longer needs to recall rules from memory to determine the current vehicle limits (see Chapter 3). A simple and commonly taught heuristic was employed to determine a safe vertical speed and thus the location of the red zones: the vehicle cannot sink faster than its current altitude. For example, if the vehicle is at an altitude of 300 feet, it must sink no faster than 300 fpm in order to safely descend. This heuristic holds true for all altitudes greater than or equal to 100 feet at which point 100 fpm remains the minimum sink rate. A higher fidelity heuristic may be employed in future versions of the VAVI if necessary however this simple yet reasonable heuristic demonstrates the concept of visualizing safety constraints.

4.2.3 Time to Touchdown Clock

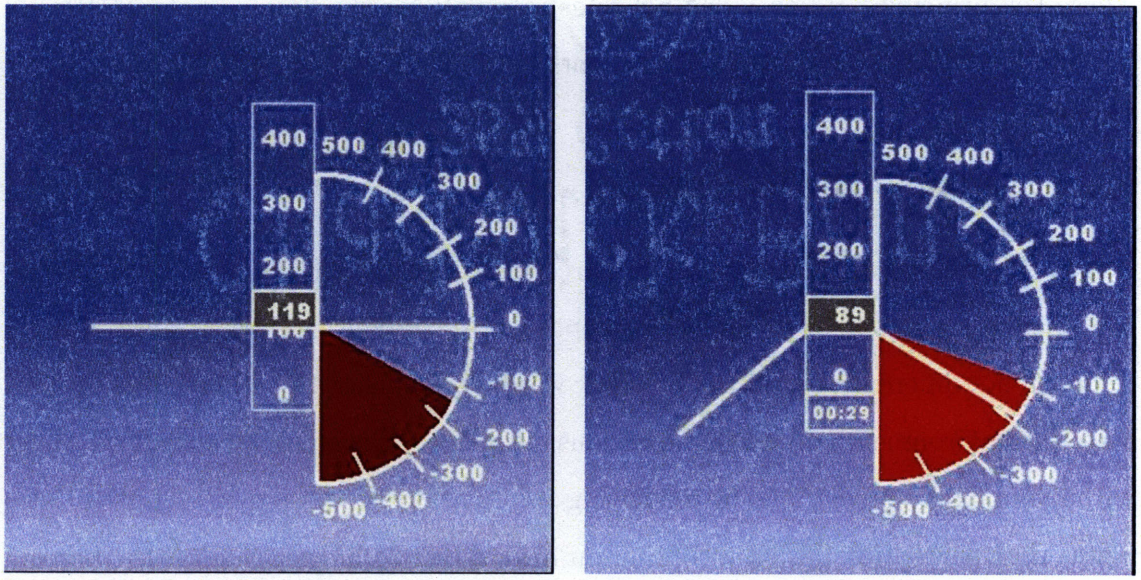
The box below the altitude bar is the estimated time to touchdown as a function of the current altitude and current sink rate. This box only appears when the vertical speed is negative, indicating a descent. For time or fuel sensitive operations, this piece of information can be critical. In the past this calculation has been a rough estimate by pilots or astronauts based on the integration of altitude and vertical speed information over time. By providing this information directly over time, mental workload can be reduced by using lower levels of cognitive control to discern goal-relevant information. This element of the VAVI satisfies design requirement 4.

4.3 Sensor Requirements

This integrated flight instrument is designed for an aircraft or spacecraft equipped with a radar altimeter and GPS sensors to provide accurate altitude and positional



(a) Nominal Ascent (b) Nominal Descent



(c) Hover (d) Unsafe Descent

Figure 4-2: Vertical Altitude and Velocity Indicator hover accuracy. The VAVI will be most effective when implemented with an instantaneous vertical speed indicator (IVSI) which displays vertical speed without the time lag normally experienced with use of a conventional vertical speed indicator. Accelerometers incorporated into the linkage allow for more instantaneous representation of vertical velocity which is critical for precision vertical landing operations and ensuring pilot trust in the data display [36].

4.4 Design Principles

Numerous studies have shown that performance can improve when displays utilize direct perception-action visual representations that allow the user to employ the more efficient processes of perception rather than the cognitively demanding processes involved when relying on memory, integration, and inference (e.g. [37, 38, 39]). Several design principles that capture this concept were applied to the design of the VAVI. These key principles are provided below as rationale for the design of the VAVI and are used to address the design requirements outlined in section 3.3.

4.4.1 Ecological Perception

Known for his research in theories of perception, psychologist James J. Gibson established the concept of ecological perception. According to Gibson, perception is a direct, non-inferential process. In other words, organisms are able to directly perceive the environment and what the various elements of the environment afford them, without making associations or mediating information processing [40]. Gibson also states that perception lies on a continuum from direct to indirect and as the perception becomes more indirect, the information available for perception is less rich and will therefore require more inference [40]. Because direct perception does not require inference, it:

- is fast, effortless, and proceeds in parallel unlike analytical cognition which is slow and error-prone [41],

- can be substituted for higher, more demanding cognitive tasks [39], and
- produces proficient performance from lower levels of cognitive control [41].

The immense power of people's perceptual abilities make utilizing direct perception an important principle in the design of user displays [41]. Direct perception-action interaction compels users, in this case pilots, to develop realistic system mental models and understand design constraints, so that they can directly perceive the system state and make correct decisions [42]. The integrated movement of the current altitude display and the vertical speed indicator provide a direct display of both pieces of information in a meaningful way, thus allowing for direct perception of critical vehicle states and corresponding actions neccessary to achieve desired states.

4.4.2 Emergent Features

One way to exploit the benefits of direct perception is to include emergent features in a display design. Bennett, Toms, and Woods defined emergent features as "high-level, global perceptual features that are produced by the interaction among individual parts or graphical elements of a display" [43, p.73]. While each graphical element of the display maintains its perceptual identity, the emergent features evolve from the interaction between the multiple elements [44, 37, 45]. Emergent features have been shown to lead to improved performance (e.g. [43, 38, 39]). The advantages of emergent features are that they:

- highlight critical relationships and goal-relevant system states [43, 38],
- map to system constraints [37, 43, 41],
- convey information about processes that change over time [38],
- allow the user to quickly and with low cognitive demand discern the current state of the system [38], and
- are highly salient [37, 38] such that the "perception of the individual elements is secondary to the perception of the object itself" [43, p.74].

The vertical speed indicator needle and its symmetric counterpart form the key emergent features of the VAVI. The VAVI arms are highly salient features that provide critical vehicle state information with a glance and correspond to specific goal-relevant states such as hovering or descending at a specific rate. Likewise, the arms also indicate whether or not vertical speed constraints are being violated by their position relative to the unsafe zone. Thus the emergent features also map directly to system vertical speed constraints. The largest benefit of the VAVI emergent features is what it affords the pilot during a vertical descent.

4.4.3 Affordances

The concept of affordances facilitates the connection between ecological or direct perception and the design of user displays. As previously described, humans directly perceive their environment, but the real value comes from perceiving the affordances of the environment. Affordances are the invariant attributes of the environment that are relevant to the entity's purposes and therefore specify the possibility for action or suggest appropriate behavior [46]. The affordances relate perception to appropriate action, eliminating the need for humans to infer the relationship between the two.

Affordances are demonstrated by the VAVI arms, which are also emergent features. The highly salient arms afford the pilot a clear understanding of vehicle state and specify action to reach the goal state or correct for an unsafe sink rate.

4.4.4 Proximity Compatibility Principle

The proximity compatibility principle (PCP), which states that to the extent that information sources must be integrated, there will be a benefit to presenting those sources either close together, in an objectlike format, or by configuring them to create emergent features [47], directly facilitates the creation of emergent features [44, 48, 49]. Two aspects of proximity explain the PCP. The first dimension, perceptual proximity, refers to the physical closeness of two display components that convey task-related information. The second dimension, processing proximity, is the extent to which two or more information sources are used as part of the same task. The level of processing proximity should drive the level of display proximity. Therefore, by moving components close together, the designer creates psychological closeness or perceptual similarity [49].

PCP has proven to lead to better performance when applied to information sources that require integration to complete a task. The cognitive benefits of employing PCP in display design include the following [49]:

- the visual search cost is decreased,
- the information access cost or internal movement of attention is decreased,
- computations required by the integration of information decreases the load on working memory, and
- the need to retain information for one source while the other source is accessed is eliminated.

The emergent features described in section 4.4.2 resulted from application of the proximity compatibility principle in which proximity was accomplished through object integration and increased physical proximity of the two sources of information: altitude and vertical speed. Specifically, combining the VAVI arms with the vertical speed indicator exemplifies application of the proximity compatibility principle.

4.4.5 Other Design Principles

Several other design principles were also considered during the design of the VAVI and are described here briefly.

The dynamic representation of quantitative analog data such as altitude and vertical speed requires the designer to consider the user's physical and conceptual representation of that data. According to Wickens and Hollands [47], altitude information is both physically and conceptually analog and therefore the altimeter should also be an analog representation. Digital formats provide the advantage of absolute high precision values, but analog representations allow for more direct perception of rates of change and relative distance from a limit of interest [47].

The principle of the moving part refers to making the motion on a display representative of the motion of the system itself [47]. In other words, "the direction of movement of an indicator on a display should be compatible with the direction of physical movement" [47, p.135] and with what is familiar to the operator. This can refer to clockwise versus counterclockwise motion, up and down motion, or others.

Both of these design principles were exploited in the design of the VAVI by representing both altitude and vertical speed in an analog form, and ensuring that the movement of those values is consistent with the normal up/down movement of altitude and the positive/negative movement of vertical speed.

4.5 Cognitive Processing Model Augmented with the VAVI

The cognitive model for managing altitude and vertical speed for a vertical landing outlined in Chapter 3 illustrated the mental steps required for pilots and astronauts to comprehend the perception of raw data from the outside world, displays, and their vestibular systems with respect to safety and mission goals using the instruments currently employed. As discussed in Chapter 3, the cognitive workload associated with completing those steps still includes numerous cognitive processes. In contrast, the introduction and implementation of the VAVI in air and spacecraft vertical displays allows for a direct perception-action sequence by taking advantage of ecological perception through emergent features created by the object integration of altitude and vertical speed information.

With use of the VAVI, pilots and astronauts can directly perceive the vehicle state relative to the safety constraints and instantaneous goals, the time to touchdown as a function of instantaneous altitude and vertical speed, altitude above the ground, and the vehicle state relative to the goal state. Thus level 1 SA is improved by effectively eliminating the mentally-taxing and often error-prone tasks associated with pulling from long-term and working memory to get to levels 2 and 3. These steps are highlighted in Figure 4-3 which compares the model with and without the VAVI and indicates those elements of the cognitive model presented in Chapter 3 that will be replaced, removed, or rearranged as a result of use of the VAVI. These changes are described below. An enlarged view of the modified model augmented with the VAVI is illustrated in Figure 4-4 and indicates the direct perception of goal-relevant information in level 1 SA through inputs provided by the VAVI.

- *Replaced*: With use of the VAVI, the need for raw data indicators such as a separate altimeter and vertical speed indicator is eliminated and replaced by the VAVI.

- *Removed*: First, the pilot's understanding of current vehicle state based on currently employed displays requires the mental integration of a digital-only or analog and digital combination representations of altitude and vertical speed. The VAVI, however, provides salient cues to relative (analog) and exact (digital) positional information, making it easy to quickly glance and comprehend the vehicle state relative to the goal state. Therefore this step from perception to comprehension is eliminated with use of the VAVI as is the perception of the altimeter value and vertical speed indicator value.

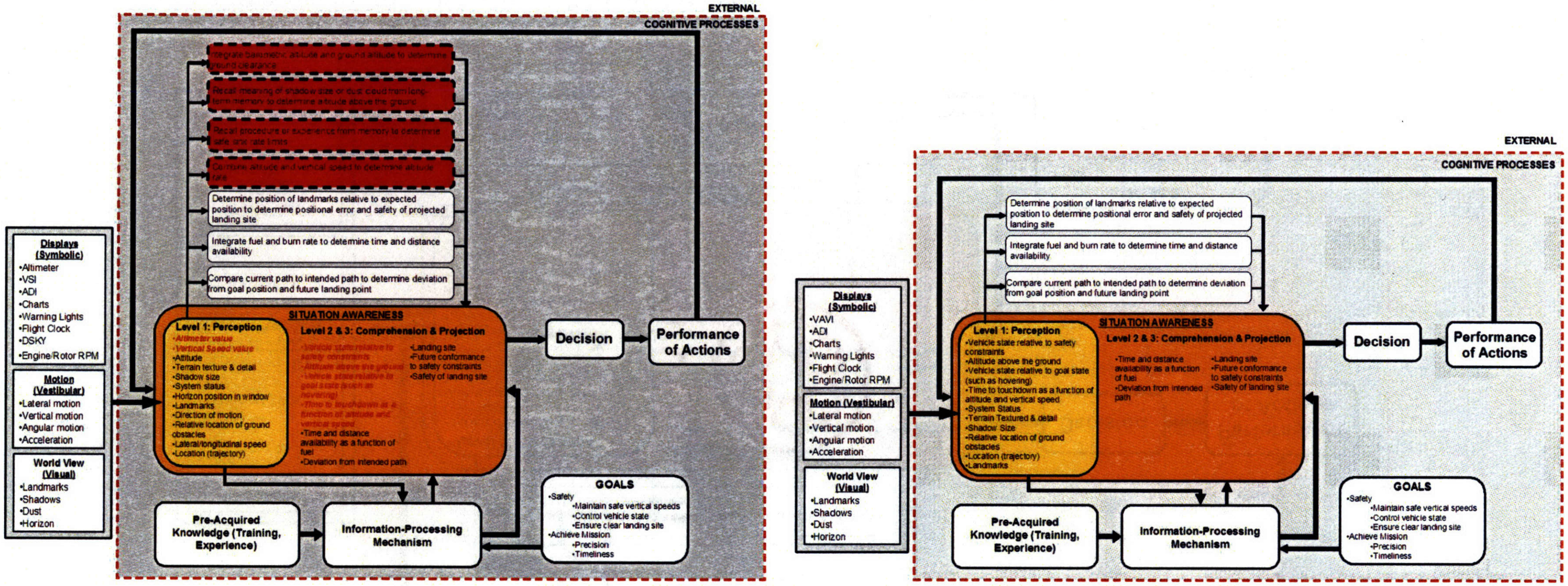
  Second, the direct display of unsafe sink rate constraints eliminates the need for a mental heuristic taught or learned through training which occupies an unnecessary human channel of information-processing. Consequently this mental step is removed from the mental processes.

  Third, by directly displaying altitude above the ground, the most important altitude during a vertical descent is salient and clearly displayed in an integrated fashion with other key parameters. Therefore pilots do not need to integrate barometric and ground altitude to determine altitude above the ground and this step is removed from the mental processes.

Finally, by allowing the automation to do the integration of altitude and vertical speed to estimate time to touchdown, this cognitive step is eliminated.

- *Rearranged*: By eliminating the above mental steps, the VAVI enables direct perception of key information. For example, the VAVI enables perception of the vehicle state relative to the safety constraints, thus moving it from level 2 situation awareness to level 1. Similarly, the vehicle state relative to a goal state such as hovering is perceived as is the time to touchdown as a function of altitude and vertical speed, and altitude above the ground. While terrain texture and shadow size will still be perceived and later comprehended to provide altitude information, that same information can be directly perceived by way of the VAVI in conjunction with the outside cues, or in their absence.

As illustrated in Figure 4-4, the VAVI does not address every cognitive process associated with the transition from perception to comprehension during a vertical descent. Hovering and vertical landings are still challenging tasks for pilots of helicopters, V/STOL aircraft, and spacecraft, but the VAVI is designed to reduce the mental workload that corresponds to the cognitive processes outlined above. In doing so, it creates a mental reserve that can be applied to more critical tasks that displays and automation cannot directly address.



(a) Without VAVI

(b) With VAVI

Figure 4-3: Cognitive models for managing altitude and vertical speed with and without the VAVI

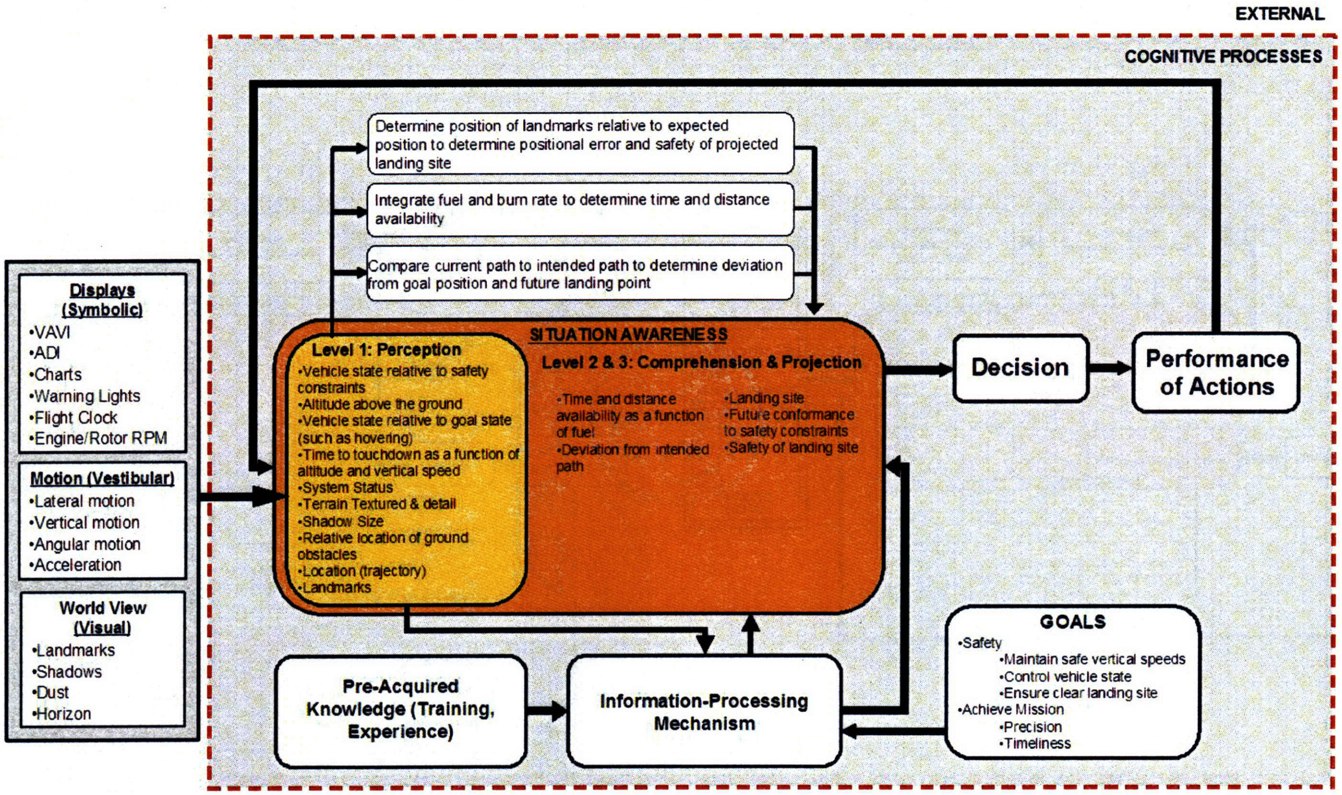


Figure 4-4: Cognitive model for managing altitude and vertical speed during a vertical landing augmented with the VAVI (adapted from [30])

Chapter 5

Human Performance Experimentation

Human performance experimentation was conducted using a commercial flight simulation software package (Microsoft Flight Simulator 2004) modified to display the VAVI in a simulated V/STOL aircraft head-up display (HUD). The experiment tested hover and landing performance hypotheses using a HUD including the VAVI, and a conventional HUD without the VAVI. The experimental method, including participants, apparatus, experimental tasks, and experimental design are described in this chapter.

5.1 Experiment Objectives

The objectives of this experiment focus on the use of the VAVI for precision vertical operations by rotorcraft, V/STOL aircraft, and spacecraft. The specific objectives are to test the effectiveness of the VAVI for improving hover and landing performance, and decreasing mental workload during these operations.

5.2 Experimental Hypotheses

5.2.1 Hover Performance

The ability to maintain a constant hover altitude was hypothesized to be most influenced by the emergent features, namely the arms of the VAVI, that indicate hover state tied directly to the hover altitude. A hover situation is clearly illustrated by outstretched and level VAVI arms. Likewise, capturing an accurate hover altitude (e.g. stop at a pre-specified altitude) is supported by the VAVI arms which are flat when a hover has been achieved. To help achieve that hover, the relative position of the arms takes advantage of ecological perception and allows the pilot to more quickly perceive and anticipate rates to determine when to terminate vertical speed to reach the desired altitude. The following hypotheses capture the expected hover performance:

- *Hypothesis 1*: the ability to maintain a constant hover altitude is expected to improve with use of the VAVI as compared to use of conventional hover and landing flight displays
- *Hypothesis 2*: use of the VAVI is expected to improve the task of capturing an accurate hover altitude

5.2.2 Landing Performance

Vertical landing performance is a function of two parameters: the ability to maintain an accurate descent rate and to maintain a safe descent rate. As the VAVI directly indicates safe descent rate limits and clearly alerts the pilots of violations of those constraints through a change in color, it was expected that the VAVI would enable more direct perception of the vehicle state in relation to the constraints. Likewise, the arms of the VAVI which indicate both a relative vertical speed direction and rate on an analog scale, clearly display exact values making it simple to realize the appropriate direction of control input for correction. The following hypotheses capture expected landing performance:

- *Hypothesis 3*: the ability to maintain a safe, dynamic sink rate is hypothesized to improve with use of the VAVI over conventional flight display components

- *Hypothesis 4*: use of the VAVI is expected to result in fewer errors when attempting to control a constant static vertical speed

5.2.3 Workload

As discussed in Chapter 3, the mental steps required to get from the data that is provided on the existing landing displays to the information needed by pilots to determine if the vehicle is conforming to safety constraints is a mentally demanding task. Since the VAVI allows for direct perception of this information and a display of the safety constraints, some of the mental steps required to comprehend important attributes of the system are eliminated (see Chapter 4). Therefore the following results are expected:

- *Hypothesis 5*: a reduction in mental workload for all hover and vertical landing tasks is expected with use of the VAVI as compared to conventional displays

5.3 Participants

A total of 31 participants participated in this experiment, 28 men and 3 women. Of those 31 participants, 9 (8 men and 1 female) did not meet the training proficiency levels outlined in section 5.7 and therefore did not move on to the test scenarios. Participants were recruited based on their rotor-wing or V/STOL pilot experience, or PC-based flight simulator experience. The participant population included students, recreational pilots, and professional pilots. Participants were compensated for their participation with an MIT Humans and Automation Laboratory t-shirt and refreshments.

The age range of qualifying participants was 12-63 years with a average age of 34. Eight of the participants had both fixed-wing and rotor-wing pilot experience, while 3 had rotor-wing and 3 had fixed-wing only experience. A total of 8 only had PC flight simulator experience. Of the 14 that had actual flight experience, 9 of them also had PC flight simulator experience. The number of hours of experience in each participant's most experienced platform (rotor-wing, fixed-wing, or PC simulator) ranged from 15-9000 with the median being 300 hours and a mean of 1175 hours. Appendix F outlines more details of the study demographics.

5.4 Test Bed

5.4.1 Apparatus

The human participant experimentation of the VAVI was conducted using a Dell 19" flat panel monitor operated at 1152 x 864 pixels and a 16-bit color resolution. The workstation was a Dell OptiPlex GX520 with an Intel Pentium 4 3.40GHz processor and an Intel 83945G Express Chipset Family graphics card. System audio was provided using standard workstation speakers.

Participants interacted with the simulator via a Saitek X45 digital joystick and throttle control, and CH Products CH Pro rudder pedals, both shown in Figure 5-1. The entire experiment apparatus was portable and designed to be positioned at any table or desk with a height adjustable chair. An example workstation is illustrated in Figure 5-2.

5.4.2 Simulation Platform

Microsoft Flight Simulator 2004 with an Abacus Military Aircraft Collector's Edition expansion pack was used to simulate an AV-8B Harrier V/STOL jet aircraft. Details about the flight simulator settings can be found in Appendix A.

Two Harrier HUDs were created from scratch: one with the VAVI (Figure 5-3) and one without the VAVI (Figure 5-4). Display elements were modeled after an actual Harrier head-up display. The VAVI display replaced any analog or digital representations of vertical velocity and radar altitude used in the HUD without the VAVI. As noted in Figure 5-3, the conventional display represents altitude digitally


(a) Joystick and Throttle (b) Rudder Pedals

Figure 5-1: Control Devices

and vertical speed both analog and digitally, but as separate components of the display.

5.5 Experimental Task

5.5.1 Scenario Commonalities

Two test scenarios were designed for this experiment. Each test scenario involved flying an AV-8B Harrier from Green State Airport in Providence, RI to Logan International Airport in Boston, MA. This route was chosen for its relatively short distance and a VHF Omnidirectional Range (VOR) navigation system which made finding the airport very simple. The flight between Providence and Boston, after takeoff and before hover and landing, lasted approximately four minutes. This allowed participants to relax after takeoff and prepare for the landing, yet not expend too much time on the straight and level portion of flight which was not of interest in this experiment. The target landing site at Logan International Airport was a helipad 100 m in diameter located between the two main runways and marked by a white circle with a large "H" in the middle. The center of the helipad was the target landing site.

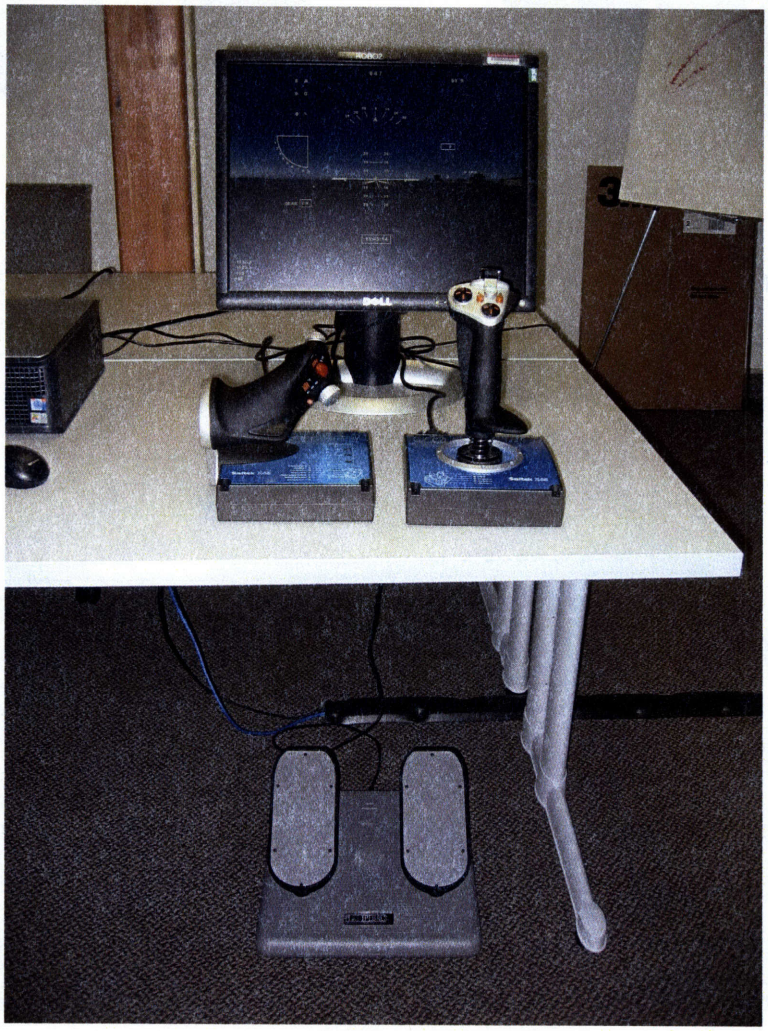


Figure 5-2: Apparatus

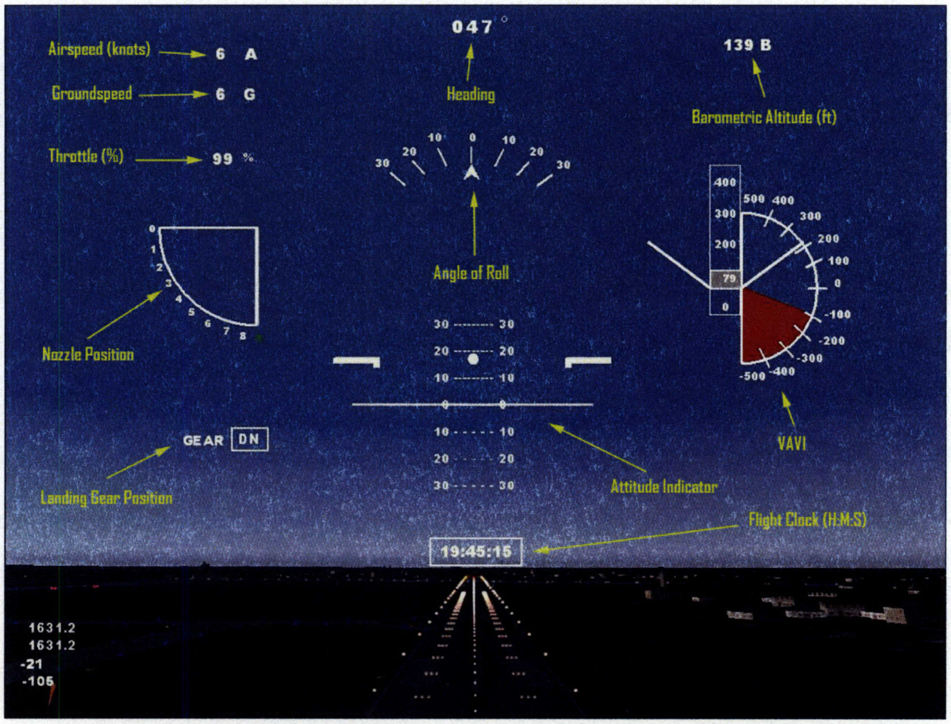


Figure 5-3: Harrier Head-Up Display with VAVI Display

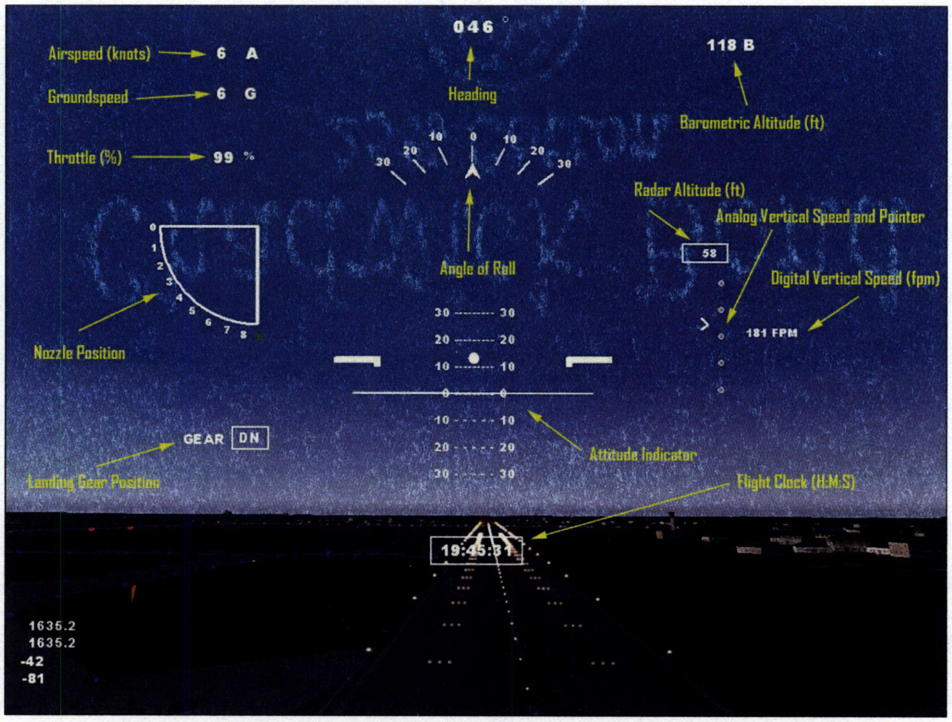


Figure 5-4: Harrier Conventional Head-Up Display

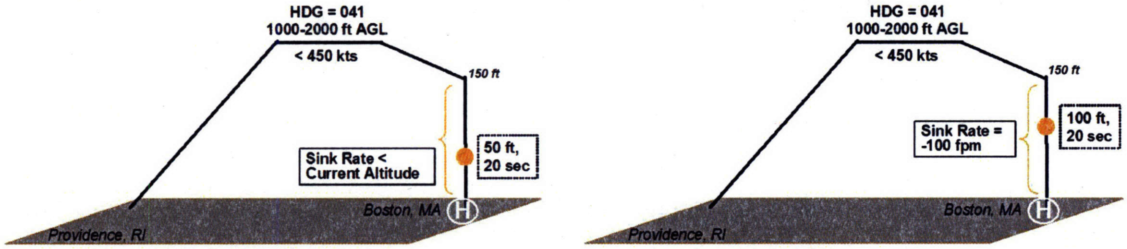
Every scenario was conducted at dusk in a simulated summer environment. This operating condition was chosen because: 1) the dark blue sky at dusk provided better contrast with the white HUD components, making it clearer for the participants, and 2) the diminishment of visual cues at this time of day in conjunction with the already reduced visual cues provided by a simulated synthetic outside view, replicated an environment in which instruments are more critical for hovering and landing tasks.

In both scenarios, participants were asked to maintain a specific heading in order to get to the Boston airport. Participants were also asked to stay within 1000-2000 feet altitude above the ground and less than 450 knots of airspeed during the straight and level portion of flight to ensure they were not too high or too fast upon approach to the airport for a vertical landing. The takeoff and straight and level flight were not of importance in either scenario.

5.5.2 Scenario Variations

The two test scenarios varied slightly during the vertical descent phase. The primary differences were the altitude at which the participants were asked to hover, and the descent rate they were asked to maintain. Both scenarios included a stationary hover (at different altitudes), while one scenario asked the participants to maintain a constant static descent rate of -100 feet-per-minute (fpm) to the landing site, the other required a dynamic sink rate, which was always less than the vehicle's current altitude (e.g. if the vehicle is at 150 feet, it should not sink any faster than 150 feet). This variation is referred to as the vertical speed heuristic. The two test scenarios in Figure 5-5 illustrate the differences between the two test scenarios. The shaded circles included on the descent indicate a hover, while the text boxes to the right of the circles indicate the altitude at which the hover should occur, and the length of time the hover should be maintained. Participants were told to hover at the assigned hover altitude, but that if they were unable to stop at that altitude on the descent, they should stabilize out as soon as they could and begin their hover at that altitude rather than try to climb back up to the assigned hover altitude. They were also told to indicate to the experimenter when they wanted to begin their hover and the experimenter informed the participant when 20 seconds had passed.

Table 5.1 outlines the flight tasks during the two test scenarios and highlights the differences between them. Participants were not given a priority for these task objectives.



(a) Test Scenario 1 (b) Test Scenario 2

Figure 5-5: Experimental Test Scenarios

Table 5.1: Flight Tasks

Flight Task	Objectives	Test 1	Test 2
Conventional Takeoff	None	x	x
Cruising	None	x	x
Hover	Maintain precise commanded altitude	x	x
	Capture accurate commanded altitude	x	x
Vertical Landing	Maintain accurate static descent rate		x
	Maintain accurate dynamic descent rate	x	
	Maintain precise vertical speed control	x	x

5.6 Experimental Design

This experiment was a 2(Display) x 2(Flight Task) mixed design study within-subjects on the flight task factor, and between-subjects on the display factor.

5.6.1 Independent Variables

Two independent variables were of interest in this experiment: instrument display component and flight task. Instrument display component refers to the HUD that participants used throughout the experiment. Participants either saw the VAVI HUD illustrated in Figure 5-3 or the conventional HUD illustrated in Figure 5-4. Therefore, this two level factor was a between-subjects variable. The flight task factor included hovering and landing, was a within-subjects variable such that every participant was asked to perform both hovers and landings.

5.6.2 Dependent Variables

Several dependent variables were used in this experiment to measure hover and landing performance and workload. Each of those variables is described in detail in this section.

Hover Accuracy

Hover accuracy addresses the participant's ability to capture a commanded hover altitude, and addresses hypothesis 2. Stopping and hovering at the desired hover altitude is an important skill that requires the use of accurate altitude and vertical speed information. Hover accuracy is measured as the difference between the commanded hover altitude and the actual hover altitude. The actual hover altitude, defined as the altitude that the participant tried to maintain, was determined to be the altitude at the time that the participants indicated they were beginning their hover. For this measure, a smaller value corresponds to better performance.

Hover Precision

Hover precision addresses hypothesis 1 which corresponds to the ability to maintain a precise hover. Deviations from the actual hover altitude are captured using a root mean square error. The root mean square error, shown in Equation 5.1, is a common measure of success that gives the error value the same dimensionality as the actual and desired values [50]. The smaller the RMSE, the better the performance. In the measure of hover precision, the "desired" variable corresponds to the altitude at the first second of the self-initiated 20 second hover and "actual" corresponds to the altitude at every second during that 20 second interval.

$$RMSE = \sqrt{\frac{\sum(actual - desired)^2}{n}} \tag{5.1}$$

Vertical Speed Precision

Vertical speed precision refers to the precision control of the vertical speed during the descent. This measure addresses the vertical descent hypotheses 3 and 4 and refers to the ability to maintain both a dynamic and static descent rate. The ability to maintain a static descent rate was also measured using a RMSE, as described in Equation 5.1. The RMSE of vertical speed from the completion of the hover to landing was calculated. Figure 5-6 illustrates how the static descent rate was analyzed using an example vertical speed profile. The solid straight line at -100 fpm indicates the desired vertical speed and the dotted lines on either side of that line represent ± 10% of the desired vertical speed. FAA practical test standards do not explicitly outline a rate of closure or vertical speed control standard, so ± 10% was determined to be a reasonable range based on the results of this experiment. Participants were not penalized for being within 10% of the commanded static descent rate (Figure 5-6A), and participants were also not penalized for having a positive ($\geq$ 0 fpm) vertical speed (Figure 5-6B) indicating that they were climbing and not descending. To prevent penalizing the participants for having a positive vertical speed, those data log entries corresponding to a positive vertical speed were not considered in the RMSE calculation. Finally, those vertical speeds that were outside of the 10% range were penalized only for their difference from the ± 10% range around the commanded speed (Figure 5-6C).

The measure of a participant's ability to maintain a dynamic sink rate used a similar approach as depicted in Figure 5-7. In this case, participants were not penalized for being within ± 10 feet per minute of the current commanded vertical speed (Figure 5-7A), which is equivalent to the negative current altitude. Again, any vertical speed outside of this range was penalized only for its deviation from the outer limit of the range (Figure 5-7C). Like the measure of static descent rate, participants were

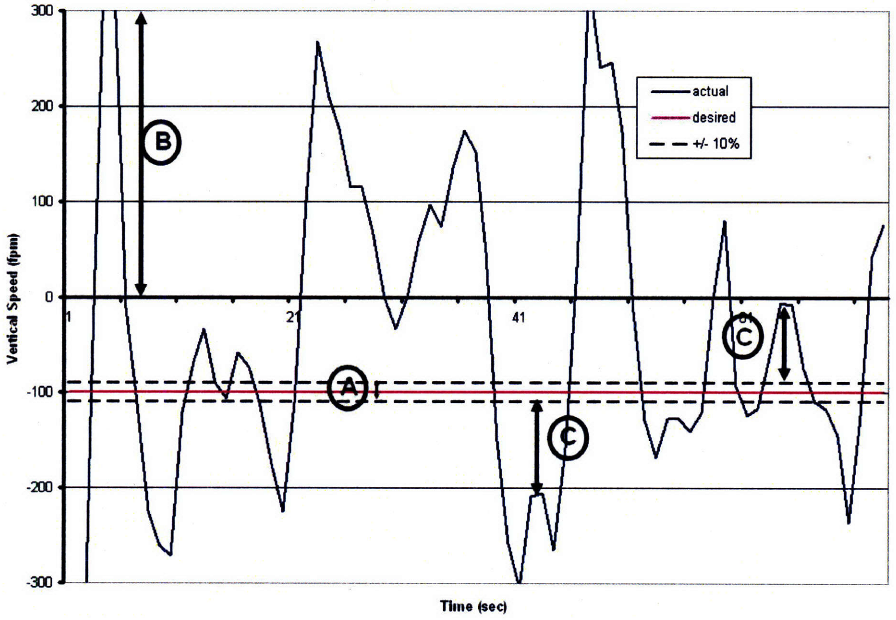


Figure 5-6: Static Vertical Speed Analysis

not penalized for having a positive vertical speed (Figure 5-7B) and those values were not included in the RMSE calculation.

Descent Duration Error

The descent duration is a measure of the comparison between the time that it should have taken the participant to descend, had they descended according to the commanded dynamic or static vertical speed heuristic, versus the actual time of descent. This dependent variable is another measure of landing performance which captures the participants' overall ability to maintain a specified descent rate. A smaller value for this measure indicates better adherence to consistent accurate vertical speed control.

Workload Measures

To measure subjective workload, participants rated their perceived mental workload on a ten-point scale, with 1 corresponding to minimal to no mental workload, and 10 corresponding to the highest mental workload the participant has ever experienced.

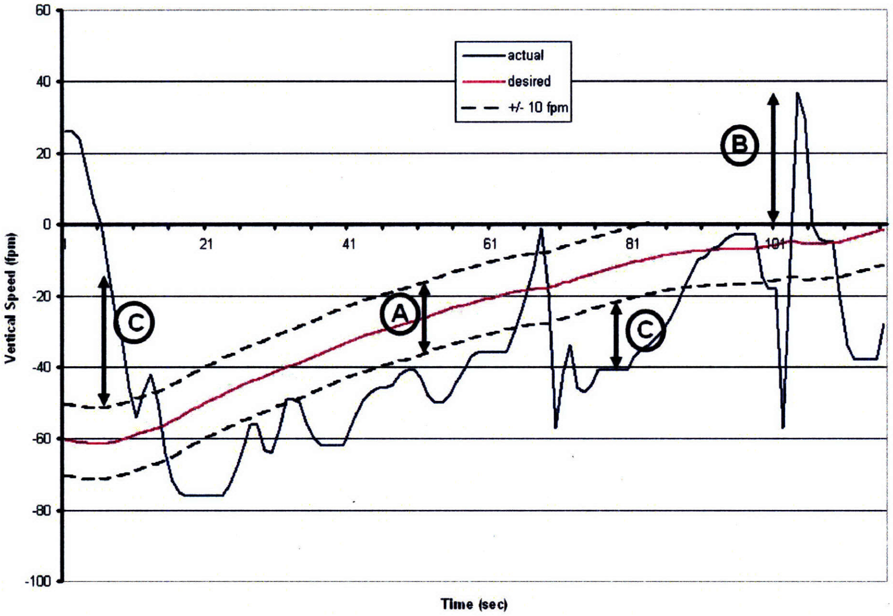


Figure 5-7: Dynamic Vertical Speed Analysis

A ten-point scale was chosen to mimic the ten-point mental demand scale associated with the NASA TLX subjective workload measure.

5.7 Procedure

Participants were first welcomed by the experimenter and given a brief introduction to the experiment. Participants then completed a signed consent form (Appendix B), followed by a demographic survey which gathered information regarding previous flight or flight simulator experience (Appendix C). Participants were then given a tutorial on a set of PowerPoint slides that detailed the purpose of the experiment and described the Harrier and the specifics of the joystick and rudder pedals. Tutorials (Appendix D) were created for each of the two types of flight instrument displays (VAVI or conventional) and each participant saw only the tutorial relevant to the HUD they would utilize throughout the experiment. The experiment tutorials took approximately 10-15 minutes to complete.

Participants were then given a series of training lessons to learn how to fly the simulated Harrier. These lessons involved first viewing a conceptual flight task lesson on the tutorial slides, then practicing the flight task using the simulator experimental apparatus. All participants had up to 50 minutes to demonstrate their proficiency at each of the specified tasks (hovering and vertical landings). Table 5.2 outlines the proficiency level required for each task in order to move on to the test scenarios. Generally participants took 90% of the entire training time to reach the proficiency levels.

Table 5.2: Training Proficiency Measures

Task	Proficiency
Hovering	Maintain a commanded hover altitude within +/- 10 ft for 30 seconds
Vertical Landing	Land at the Boston airport Perform a controlled descent Do not crash

Following the training and demonstration of proficiency, participants completed the two test scenarios described in the previous section, each lasting approximately 10 minutes. Before beginning the tests, participants were informed that their performance during takeoff and straight and level portions of flight would not be measured, but hovering and vertical landing performance would be measured relative to the objectives outlined in Table 5.1. During each test scenario, the figure accompanying it (see Figure 5-5) was taped at the bottom of display as a reminder of the specific goals for each flight. Participants were presented the test scenarios in randomized order to prevent a possible order effect. At the completion of each test scenario, participants filled out a ten-point workload survey. Once the experiment was completed, feedback was solicited about the display and the experience through a semi-structured interview to help guide the discussion (see Appendix E for initial interview questions). The two test scenarios followed by the workload scales took a total of 30 minutes on average. The entire experiment took roughly 90 minutes total.

5.8 Data Collection

During testing, key flight parameters such as altitude, heading, pitch, bank, vertical velocity, airspeed, latitude and longitude, and others were recorded to a data log file every second using flight data recorder software. The experimenter also observed each test participant during their test scenarios and noted any interesting behavior to include gaze or focus, body posture, and comments made throughout or during a specific task.

Chapter 6

Results

This chapter presents the statistical results of the experiment described in Chapter 5. The experiment included two independent variables: Head-Up Display Instrument (VAVI or conventional) and Flight Task (hovering or landing). Numerous dependent variables were considered in the analysis of the data in order to capture and measure hover performance, landing performance, and workload as described in Chapter 5. Each of those variables are discussed and presented in this chapter.

6.1 Overview

The dependent measures used to analyze the two flight tasks were often different for each task because the dependent measures used to measure hover performance were not extendable to landing performance and vice versa. Therefore, the general linear model used for this analysis included both single and two-factor analysis of variance as applicable. Appendix G gives a summary with more details of all of the statistical tests used in the analysis of these results. The independent factors were considered to be fixed and the participants were a random factor. For all reported results, $\alpha = 0.05$ unless stated otherwise.

6.2 Hover Performance

6.2.1 Hover Accuracy

As outlined in Section 5.6.2, the measure for determining the participants' ability to capture a commanded hover altitude was hover altitude error, or the error between actual hover altitude and commanded hover altitude. One-way analysis of variance (ANOVA) results indicated that there was no significant difference in hover accuracy between flight display levels (F(1,34) = 0.425, p = 0.519). A square root transformation of the data with a 0.5 correction due to zero values was required to meet homogeneity and normality assumptions for the ANOVA test. The boxplot in Figure 6-1 shows the median hover altitude error as well as the quartiles and extreme values for each flight display level, and Table 6.1 summarizes the key statistics.

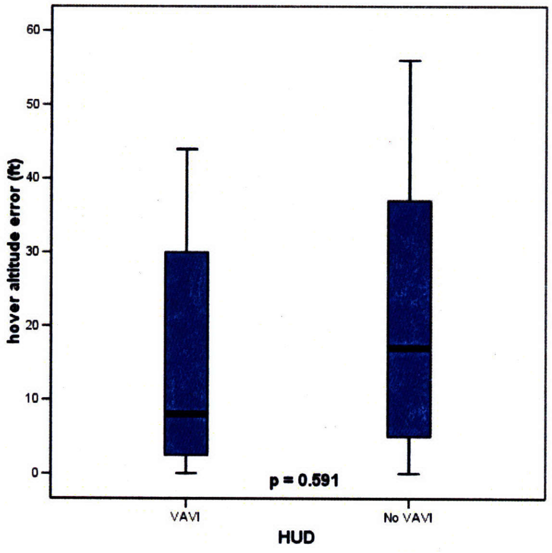


Figure 6-1: Hover altitude error

Table 6.1: Hover Altitude Error Summary

	Mean	Median	Std Dev
VAVI	17.16	8.00	16.43
No VAVI	20.59	17.00	18.35

6.2.2 Hover Precision

A one-way ANOVA performed on the root mean square error (RMSE) of the hover altitude during the 20 seconds that the participants informed the experimenter that they were hovering indicated that there was also no significant difference in hover precision between flight display levels ($F(1,34) = 1.484$, $p = 0.231$). As there were normality violations, a square root transformation of the data was required to meet homogeneity and normality assumptions. Figure 6-2[1] illustrates the comparison between the two flight display levels and Table 6.2 outlines the key statistics.

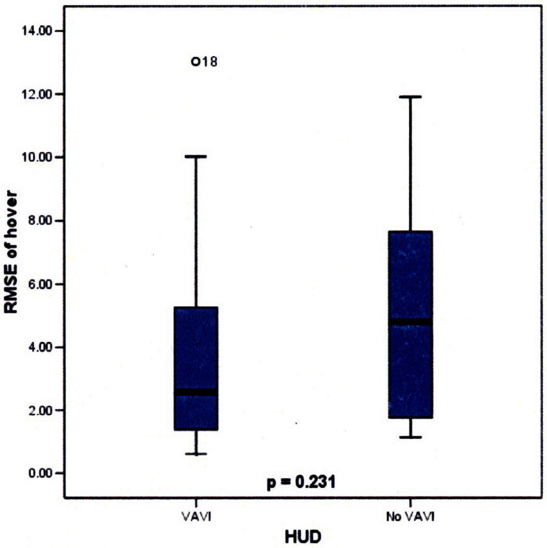


Figure 6-2: RMSE of hover altitude

Table 6.2: RMSE of hover altitude summary

	Mean	Median	Std Dev
VAVI	3.73	2.57	3.29
No VAVI	5.11	4.80	3.41

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[1] "18" is a statistical outlier and refers to the spreadsheet line, not the dependent measure value

6.3 Landing Performance

6.3.1 Vertical Speed Precision

The RMSE of vertical descent speed was analyzed as a 2x2 ANOVA, treating flight display (VAVI or No VAVI) as the primary factor, and vertical speed heuristic (dynamic or static) as the secondary factor. Vertical speed heuristic refers to whether participants were asked to hold a constant (static) vertical speed or a changing (dynamic) vertical speed during their descent. A reciprocal transformation of the data was necessary to meet homogeneity and normality requirements. The RMSE of vertical speed was significantly lower with the VAVI ($F(1,30) = 5.484$, $p = 0.026$), but there was no significant difference between vertical speed heuristics ($F(1,30) = 0.023$, $p = 0.879$). There was no significant interaction between the factors. Figure 6-3 illustrates the comparison between the flight display levels and test scenarios. Table 6.3 outlines the respective means, medians, and standard deviations for each test with and without the VAVI.

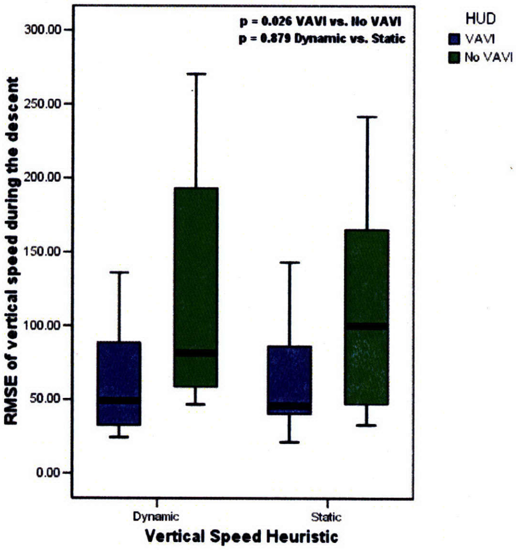

Figure 6-3: RMSE of vertical descent

Table 6.3: RMSE of vertical speed summary

	VAVI		No VAVI	
	Dynamic	Static	Dynamic	Static
Mean	62.50	64.78	122.99	111.39
Median	49.07	45.54	81.73	99.79
Std Dev	41.69	40.77	91.14	80.07

6.3.2 Descent Duration Error

The descent duration error was defined as the difference between the desired descent duration and the actual descent duration, normalized by the total duration. It measures the "smoothness" of the descent. Non-parametric tests were used to determine differences between flight display level and vertical speed heuristic. A Mann-Whitney U test was conducted that compared flight display levels. There was no difference in this landing performance measure between VAVI and non-VAVI users (p = 0.790). A Wilcoxon Signed-Rank test was performed on the data to compare the vertical speed heuristic that participants were asked to use. Results show that there is a highly significant difference between heuristics (p = 0.001), indicating that performance was much better when participants were asked to maintain a constant static vertical speed on their descent. This difference is illustrated in Figure 6-4 and outlined in Table 6.4.

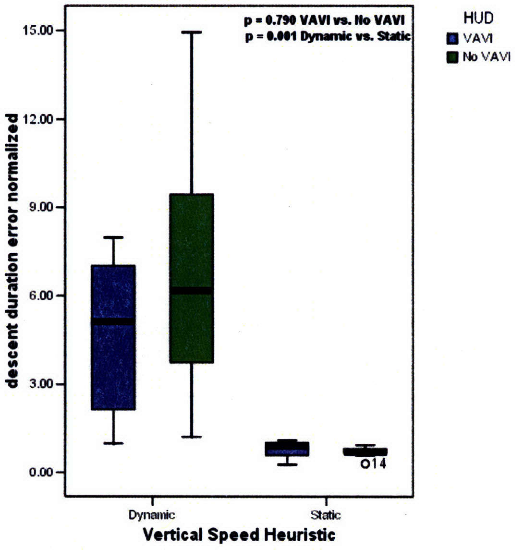

Figure 6-4: Descent Duration Error

Table 6.4: Descent Duration Error Summary

	VAVI		No VAVI	
	Dynamic	Static	Dynamic	Static
Mean	4.70	0.80	6.96	0.71
Median	5.12	0.91	6.18	0.70
Std Dev	2.64	0.30	4.76	0.19

6.4 Workload

Subjective workload was measured through use of a ten-point workload scale that was modeled after the NASA TLX mental demand measure. Participants completed a workload survey following each test scenario.

6.4.1 10-Point Workload Scale

The 10-pt anchored workload scale associated a "10" with the highest mental workload that a person has ever experienced, and a "1" with minimal to no mental workload. A non-parametric Mann-Whitney U test was conducted across all test scenarios to compare flight display levels. The U test indicated marginal significance ($p = 0.108$)[2], but the boxplots in Figure 6-5 illustrate that the median values for the 10-pt workload rating is higher without the VAVI in both test scenarios (see Table 6.5).

A Wilcoxon Signed-Rank test was used to analyze the differences between test scenarios and showed no significance between vertical speed control heuristics ($p = 0.642$).

Table 6.5: 10-pt Subjective Workload Rating Summary

	VAVI		No VAVI	
	Test 1	Test 2	Test 1	Test 2
Mean	5.13	5.00	5.70	5.70
Median	5.00	4.50	7.00	6.50
Std Dev	1.51	1.35	2.50	2.41

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[2] α=0.1 for non-parametric tests

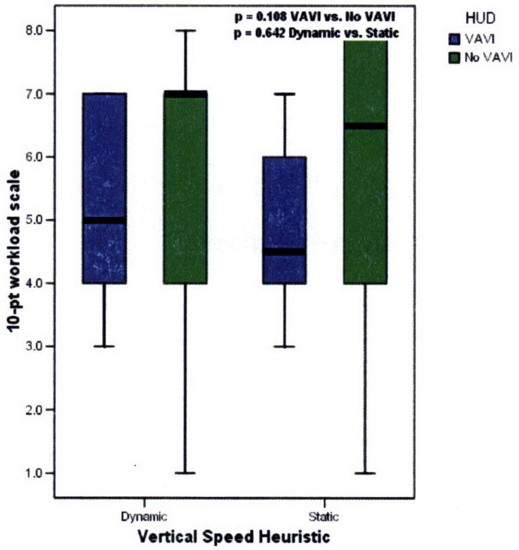


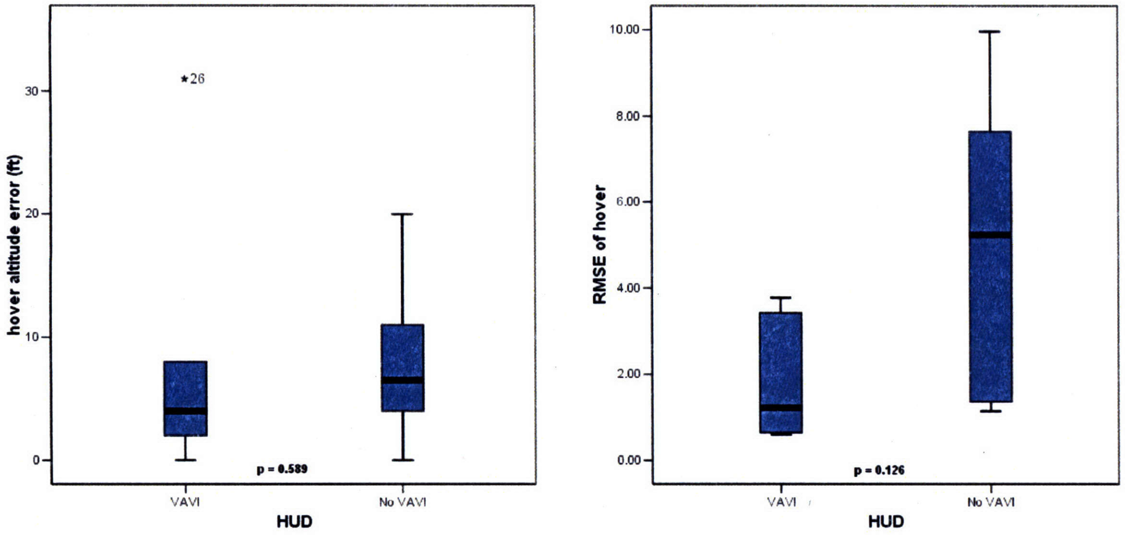
Figure 6-5: 10-pt Workload Scale Boxplot

6.5 Top Performer Subset Analysis

A further analysis of all the dependent variables was conducted on the top three performers from each flight display group (VAVI and No VAVI). The top performers were determined based on their average ranking across all dependent measures as illustrated in Appendix H. This analysis was conducted to investigate the performance between participants who set themselves apart from the rest of the participant pool by demonstrating controlled and expert flight performance. This subset analysis may more closely represent the use of these displays in operational aircraft, since these participants were able to control the aircraft in a simulated environment similar to what would be expected from highly trained pilots. Using only those six participants who set themselves apart from the majority of the participants, the same analyses were conducted on all dependent measures discussed above. Non-parametric analyses were used for all dependent measures of this participant subset.

In this subset of expert participants, hover accuracy continued to show no significant difference between flight displays (Mann-Whitney, p = 0.589). Hover precision, however, showed a marginally significant difference in flight displays (Mann-Whitney,

$p = 0.126^3$), as compared to the non-significant difference previously outlined for all participants ($p = 0.231$). As illustrated in Figure 6-6b, expert users with the VAVI showed improved ability to maintain a desired altitude as compared to the conventional display of vertical speed and altitude. Table 6.6 summarizes the key statistics for hover performance of this participant subset.



(a) Hover Accuracy

(b) Hover Precision

Figure 6-6: Top Participants Hover Performance Measures

Table 6.6: Top Participants Statistics Summary, Hover Measures

	VAVI			No VAVI		
Dep. Measure	Mean	Median	Std Dev	Mean	Median	Std Dev
Hover Accuracy	8.17	4.00	11.50	8.0	6.50	6.96
Hover Precision	1.81	1.21	1.42	5.07	5.23	3.87

As indicated in Table 6.9, vertical speed precision was still highly significant (Mann-Whitney, $p = 0.015$) between flight display levels in this subset, and still not significant between vertical speed heuristics (Wilcoxon, $p = 0.600$). The plot of means illustrated in Figure 6-7b demonstrates the consistent improvement in performance across both vertical speed control tasks. The consistent VAVI results between vertical speed heuristics indicate that while the control of a dynamic vertical speed

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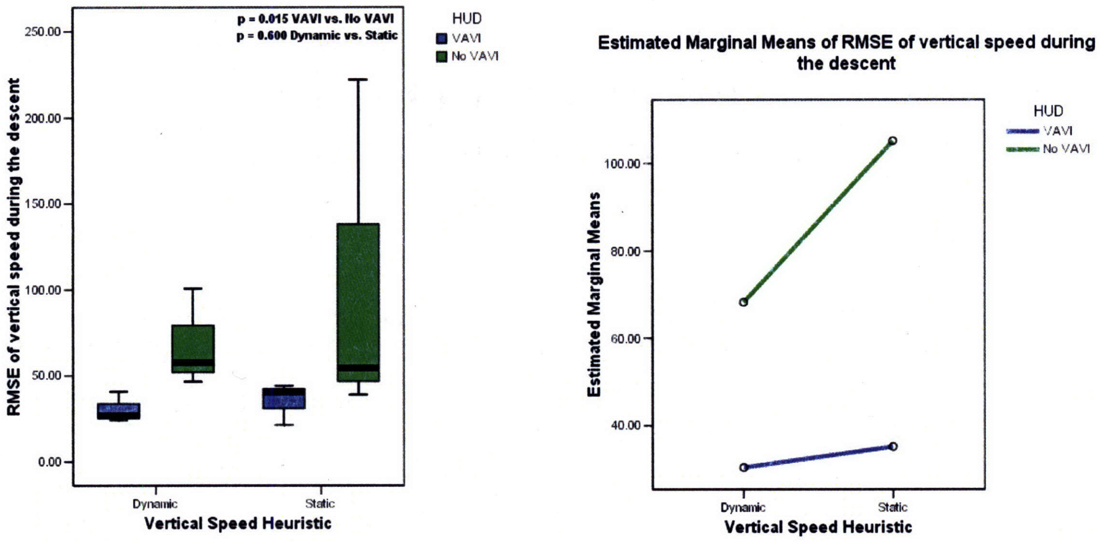
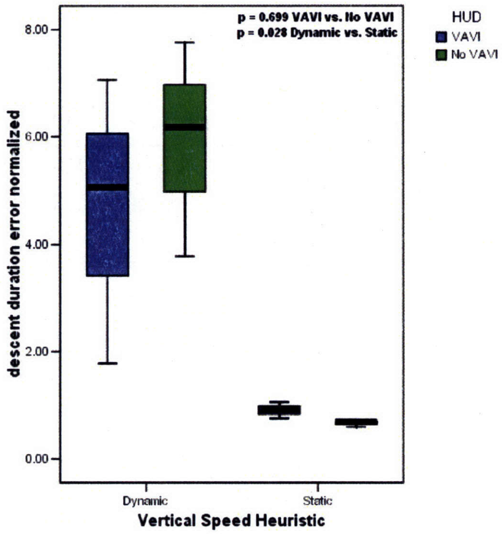
[3] α=0.1 for non-parametric tests



(a) Vertical Speed Precision (b) Vertical Speed Precision Means



(c) Descent Duration Error

Figure 6-7: Top Participants Landing Performance Measures is more difficult than that of a static vertical speed, the VAVI makes both tasks consistently easier (as illustrated by better performance and significantly less variation) as shown in Figure 6-7a. Results for descent duration error were consistent with the findings for all participants: there was no significance between flight display levels (Mann-Whitney, p = 0.699), and a significant difference between vertical speed heuristics (Wilcoxon, p = 0.028). Tables 6.7 and 6.8 summarize the mean, median, and standard deviation of all of the landing performance dependent measures of this participant subset.

Table 6.7: Top Participants Statistics Summary, Dynamic Vertical Speed Heuristic

	VAVI			No VAVI		
Dep. Measure	Mean	Median	Std Dev	Mean	Median	Std Dev
VS Precision	30.50	26.58	8.89	68.26	57.45	28.75
Descent Duration Error	4.63	5.06	2.66	5.90	6.18	2.00
10-pt Workload	6.00	7.00	1.73	7.33	7.00	0.58

Table 6.8: Top Subjects Statistics Summary, Static Vertical Speed Heuristic

	VAVI			No VAVI		
Dep. Measure	Mean	Median	Std Dev	Mean	Median	Std Dev
VS Precision	35.24	40.42	12.34	105.10	54.36	101.60
Descent Duration Error	0.91	0.91	0.15	0.66	0.69	0.06
10-pt Workload	5.33	6.00	1.15	7.33	7.00	0.58

Workload results show a statistically significant difference between flight displays in this expert subset (Mann-Whitney, p = 0.026) as compared to a marginally significant difference in the large participant pool (p = 0.108), and still no significance between vertical speed heuristics (Wilcoxon, p = 0.157). The boxplot in Figure 6-8 illustrates the difference in workload between flight displays. This indicates that when participants have adequate training and are comfortable and good at the vertical landing tasks, workload is reduced with use of the VAVI. Interestingly, while the quantitative results indicate that a dynamic vertical speed is more difficult to control than a static speed, participants did not perceive a significant difference in their mental workload between vertical speed conditions.

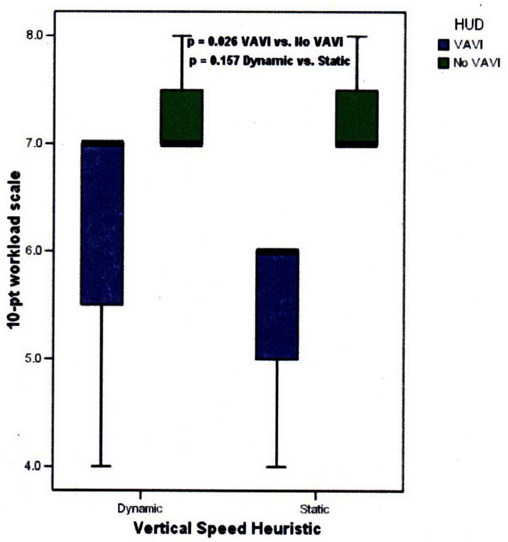


Figure 6-8: Top Participants Workload Performance Measures

6.5.1 Top Performer Summary

To summarize the performance of the top six subjects, Table 6.9 outlines the statistical significance associated with each dependent measure. More detailed non-parametric results are outlined in Appendix F. Hover accuracy, vertical speed precision, and descent duration error results were consistent with results from the large participant group. Hover precision, however, showed marginally significant improvement with use of the VAVI, while workload results strongly indicated a lower mental workload associated with the VAVI. These results indicate improved hover performance and reduced perceived workload with use of the VAVI when used by an expert subset of participants.

Table 6.9: Top Participants Summary

Dep. Measure	HUD	VS Heuristic
Hover Accuracy	p = 0.589	N/A
Hover Precision	p = 0.126	N/A
VS Precision	p = 0.015	p = 0.600
Descent Duration Error	p = 0.699	p = 0.028
10-pt Workload	p = 0.026	p = 0.157

Chapter 7

Discussion

This chapter discusses the results presented in Chapter 6 and compares them to the hypotheses outlined in Chapter 5. First, hover performance, landing performance, and workload results will be discussed in relation to the model presented in Chapter 3. Then, subjective responses gathered through a semi-structured interview will be reported and discussed.

7.1 Hover Performance

Hover performance was classified by hover accuracy and hover precision. As outlined in section 5.6.2, hover accuracy addresses the ability to capture a commanded hover altitude during a descent, and hover precision captures the ability to maintain a constant hover altitude. Though the results did not indicate any statistically significant differences between flight display factor levels at the $\alpha = 0.05$ level, they are still consistent with hypotheses 1 and 2. As outlined in Tables 6.1 and 6.2, the mean and median hover altitude error values for those participants that used the VAVI was considerably less than for those who did not, signifying a possible trend towards significance. In the analysis of the top six performers, hover precision showed marginal significance in better performance with use of the VAVI, further illustrating the effectiveness of the VAVI.

Hover performance was a difficult metric to capture because the 20 seconds during which the participants indicated to the experimenter that they were hovering, did not necessarily capture the participants' best hover performance throughout the cycle. This difficulty may have had a significant affect on the results of this dependent variable.

7.2 Landing Performance

Landing performance showed clearer results, particularly that the VAVI corresponds to significantly less vertical speed deviations for both static and dynamic sink rate control over the duration of the descent. These results are consistent with hypotheses 3 and 4 and demonstrate that average vertical speed control error over the duration of the descent is less with use of the VAVI than without. The direct perception of both relative and more precise vertical speed facilitated by the VAVI enabled more consistent monitoring of this parameter and provided a more obvious display of large or undesirable deviations in vertical speed. By displaying flight parameters relative to the goal state, the vehicle state was directly perceived and comprehended in a single step as outlined in cognitive model in Chapter 4.

The descent duration error landing performance measure illustrated a very significant difference between vertical speed heuristics despite the lack of difference between flight displays at the α=0.05 level. This exemplifies that the *consistent* control of a static vertical descent is much easier for participants than the control of a constantly changing desired vertical speed, regardless of the display that is available. This is an expected result because a constant rate of descent is easier to remember than a constantly changing one that requires adjustment. This measure can be thought of as a measure of the "smoothness" of the descent. Further analysis of the data revealed that the descent duration error for dynamic vertical speed control was most often associated with a shorter duration, meaning that participants touched down too quickly. This is also a logical and expected result.

The analysis of this variable using the top six performers illustrated a much more pronounced (though not statistically significant) difference between flight display levels in the dynamic vertical speed heuristic scenario, which is more consistent with expected results. Without a display of safe vertical speed constraints on the conventional display, participants were less aware of their excessive vertical speed, which resulted in too fast of a descent. In addition, the rapidly changing nature of variables that must constantly be tracked in the dynamic situation requires more iterations through the levels of situation awareness outlined in Chapter 3. By enabling the direct perception and comprehension of key dynamic parameters, several mental steps were removed with use of the VAVI which allowed for more appropriate aircraft control more quickly.

7.3 Workload

A subjective workload measure was used to capture the mental workload that participants associated with their tasks. Subjective workload measures can provide some information about workload, but are also difficult to employ because different people judge the meaning of the scale differently.

The results of the ten-point workload scale, which showed that the VAVI marginally corresponds to a lower mental workload than a conventional display, are consistent with hypothesis 5. The lack of difference in results between test scenarios indicates that participants perceived differences in hover altitude and vertical speed heuristic to be equivalently mentally demanding. However, across all flight tasks, those participants who used the VAVI did consistently report experiencing a lower mental workload. Since this measure was a between-subjects measure, the results suggest a decrease in perceived mental workload between flight display levels. The objective measures of hover and landing performance suggest that participants had to perform significantly less highly cognitive calculations and could rely more on perception with use of the VAVI. This allowed for more precise control and these subjective results also support that conclusion. For the expert participants, however, the difference in perceived mental workload between flight displays was statistically significant. Overall, the results indicate a lower mental workload associated with the VAVI, which is more obvious among expert participants.

7.4 Summary

Although not all dependent measures of hover and landing performance and mental workload resulted in statistical significance at the α=0.05 level, *all* of the results illustrate a trend towards improved performance with use of the VAVI as seen in summary of boxplots in Figure 7-1. Furthermore, Figure 7-2 depicts the comparison of means, medians, and standard deviations between flight display levels for all dependent measures and test scenarios. The similar line trends which illustrate better performance with the VAVI across all dependent variables, provide another indication of the consistent and positive results with the VAVI.

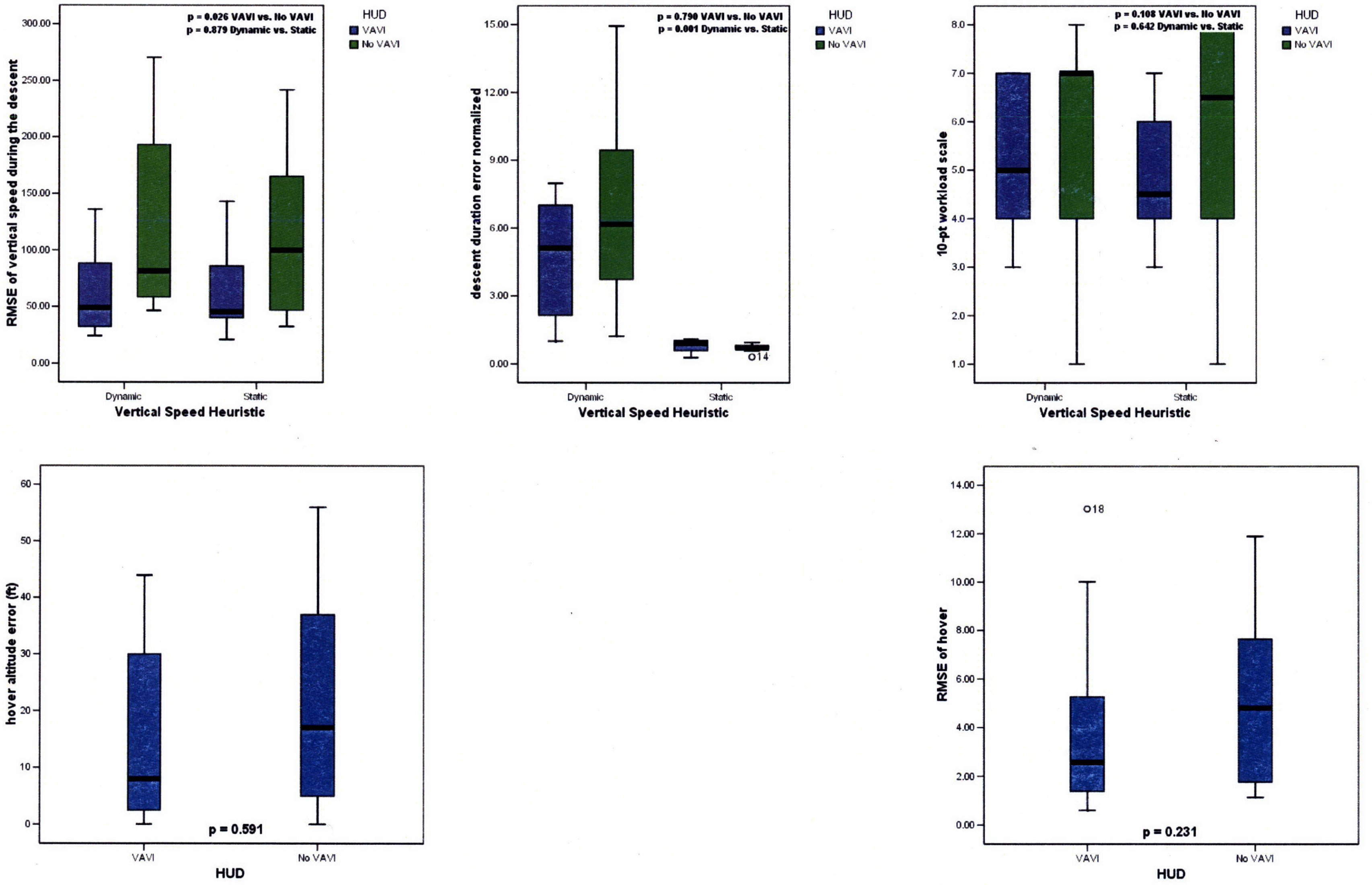
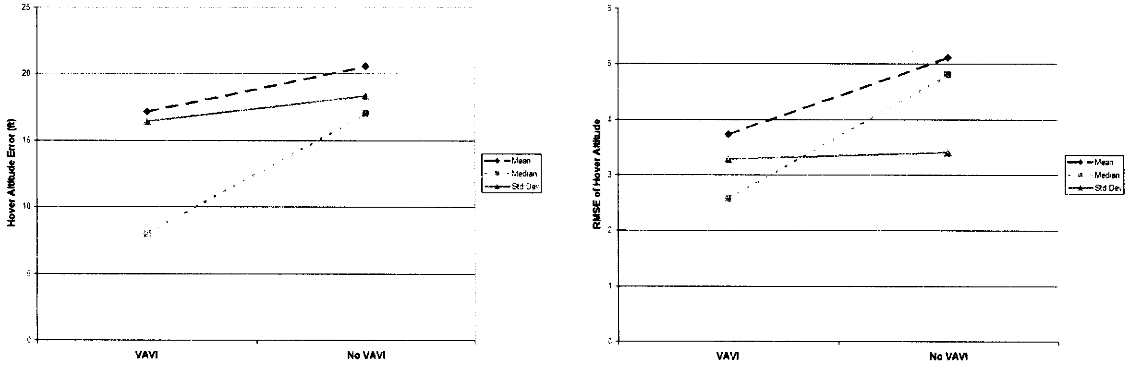
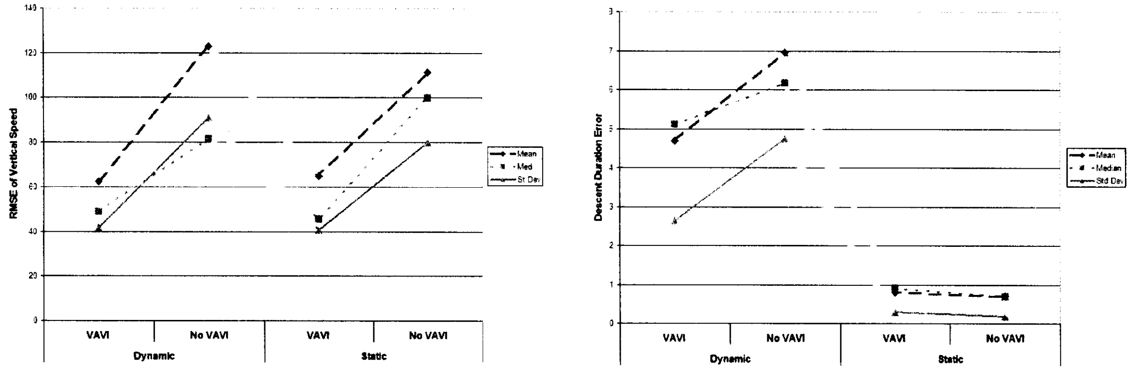


Figure 7-1: Performance Measures Summary



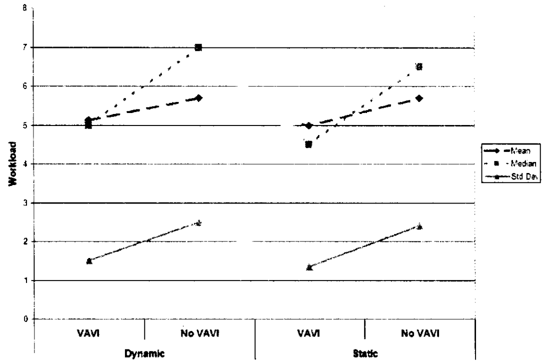
(a) Hover Accuracy

(b) Hover Precision



(c) Vertical Speed Precision

(d) Descent Duration Error



(e) Workload

Figure 7-2: Statistics Summary

7.5 Subjective Responses

General feedback was elicited from the participants upon completion of the experiment. The specific questions that were used for discussion are outlined in Appendix E. The responses pertaining directly to the display of vertical speed and altitude, as well as other comments about the experiment and display as a whole are discussed here.

7.5.1 Usability Survey

Those participants who used the VAVI indicated that they found several characteristics very helpful. Specifically, many of the participants reported that the red zone "jumped out" at them when it changed color and indicated a necessary increase in throttle. In this way, the VAVI indicated not only the system constraints, but also mapped to a specific control input to fix the vertical speed violation. This observation supports the model in Chapter 4 which illustrates the reduced mental steps necessary to quickly transition to an appropriate action as a result of good situation awareness with use of the VAVI. Many of the participants also indicated that the VAVI was specifically helpful for trying to maintain an accurate hover altitude by trying to keep the VAVI arms level. When asked how they used the VAVI, several participants said they looked at the direction of the needle to get a relative sense of vertical speed. One participant specifically stated that he used the VAVI to keep from descending too fast. Another stated that he found the fact that the arms moved up and down with the current altitude grabbed his attention during flight and made him aware of his current altitude.

Roughly half of the participants indicated that they only used the right arm, while the other half said they used both arms of the VAVI as a unit. Of those that used both, several indicated that they used it in the periphery of their vision. Of those that did not use the left arm, two indicated that they did not even notice it, and only one found the left arm distracting. Almost all of the participants reported that the VAVI was not useful during the straight and level portion of flight due to the quick up and down movement of the vertical speed indicator arms with changes in pitch. The VAVI was originally only intended to be displayed during hover and landing maneuvers and not en-route flight, but simulation constraints drove the need to display it all the time in these experiments. Moreover, many participants reported that when the arms were pegged up or down (i.e. at > 500 fpm or < -500 fpm) it was difficult to tell which direction they were pointed with a glance and thus were not referenced as frequently when they were in this position, even if this occurred during the vertical portion of flight. Similarly, one participant pointed out that when vertical speed with less than 100 or -100 fpm, it was difficult to tell an exact vertical speed. Current displays, however, do not provide vertical speed information to any more precision than the VAVI.

Participants in the conventional display group also discussed the processes that they went through to understand vertical speed and position information. Three participants stated that they only used the digital readout of vertical speed, while only one preferred to only use the analog. The majority looked at the analog scale first and then to the digital value for more precise information depending on the position of the pointer along the analog scale. One participant indicated that he would like the digital value to be in the pointer so that he would not have to move back and forth to line up speed with altitude. He followed this comment by stating that "the trick is to be able to see instantly, the position of things." Four of the participants who used the conventional display specifically reported that they found the tasks difficult because they focused on one variable and another would slip. One participant indicated that by the time he realized that his vertical speed was no longer under control, he was already on the ground. He suggested changing the color of the altimeter box when the altitude dropped below an appropriate pre-determined altitude to indicate that the control of vertical speed is important.

Interestingly, the majority of comments pertaining to possible improvements of the conventional display were directly related to VAVI characteristics specifically designed to eliminate the cognitive demand associated with vertical operations. Since all of the information is combined, the VAVI prevents the need to focus on one parameter to the detriment of another as many of the participants reported while using the conventional display. In addition, several of the conventional display participants specifically indicated the need for some sort of alerting method which the VAVI directly addresses through the use of the unsafe sink rate zone.

When asked what other information they wished they had to help them with the vertical descent and hovering, the participants indicated they needed longitudinal and lateral movement and position in relation to the target landing site. Many participants wished they had a top-down view of the landing site in order to see below them. One participant reported that he would like to have an altitude bug which he could set to indicate the altitude at which he would like to hover so that he did not have remember and remind himself of this information. This feature was originally included in the VAVI design, but it was not included in the VAVI experimentation due to software implementation constraints. An example of this feature will be depicted in the next section. Two other participants also indicated that they would have liked airspeed to be an analog display as well.

7.6 Recommendations

7.6.1 Design Recommendations

Based on comments elicited at the completion of the experiment, the following VAVI design recommendations should be considered for future versions of the VAVI.

- When vertical speed exceeds ± 500 fpm, arms should provide an obvious display of the vertical speed direction. One suggestion is to use the left, symmetric arm to indicate position through a change in color, the addition of an arrowhead (Figure 7-3a), dotting of the line, or perhaps flashing.

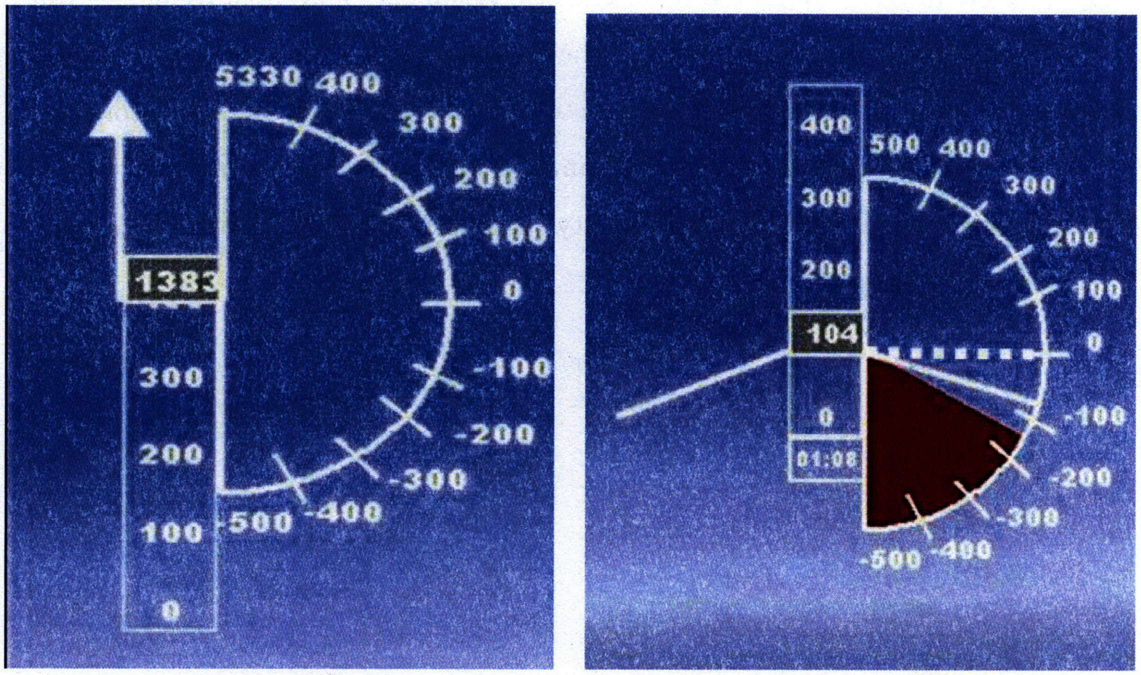
- To provide a better visualization of vertical speed indicator needle angle and thus more precise vertical speed information, a dotted reference line at 0 fpm could be added as illustrated in Figure 7-3b.

- When vertical speed exceeds ± 500 fpm, the digital readout should remain consistent with the analog scale discretization of vertical speed. For example, instead of displaying the exact digital value of vertical speed once it exceeds the analog scale, the digital value should only increase in increments of 100 fpm as is consistent with the analog scale.

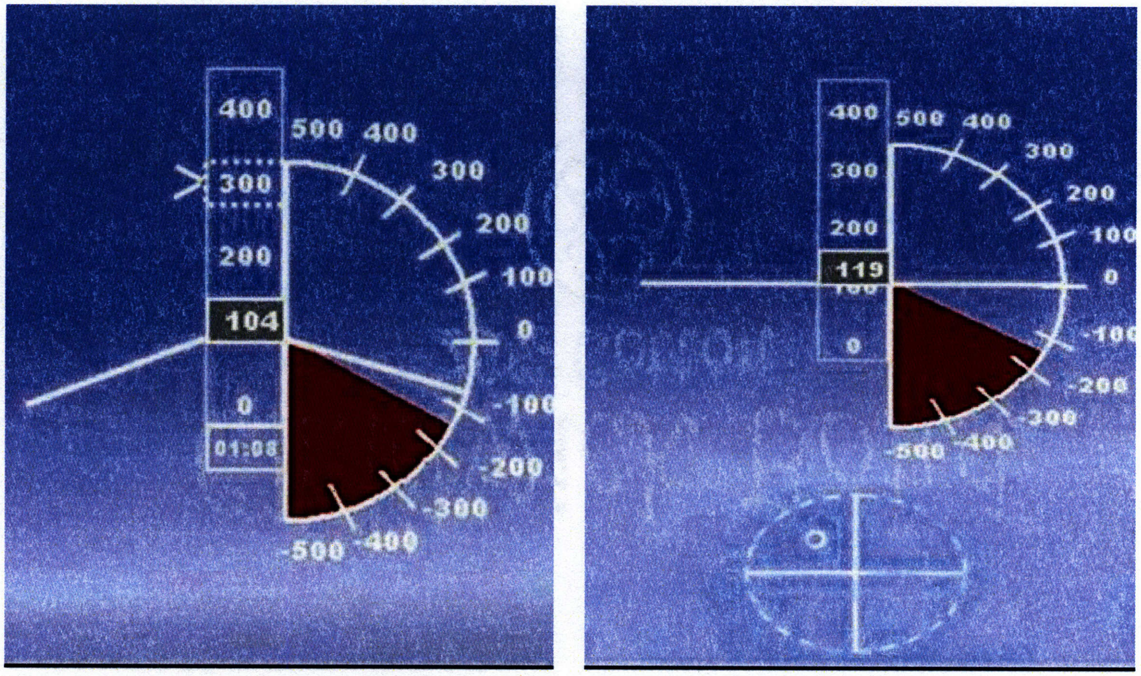
- An altitude cue which can be set by the user could be included as an optional feature for accurate hovering. The cue would provide a reminder of the target hover altitude. One option is to highlight the desired hover altitude with a dotted box around it, include an arrow-like cue, or both, as illustrated in Figure 7-3c.
- The VAVI should be used in conjunction with a display of lateral and longitudinal position relative to the target landing site. This display would required GPS technology to map positional error. This concept is depicted in Figure 7-3d where the center of the cross is the target landing site and the small circle is the aircraft position relative to the target.
- To further integrate important landing information, a heading arc could be incorporated over the top of the VAVI.
- The VAVI could include a display of acceleration to provide additional directional and rate information.

7.6.2 Future Experiment Recommendations

PC flight simulators provide an excellent starting point for the test and evaluation of display concepts. However, flight simulation cannot replace real aviation. In this experiment, numerous participants with vertical aircraft flight experience were unable to gain adequate proficiency with the PC simulator, which they generally attributed to the lack of visual cues and haptic feedback. Participants with a large amount of video game experience had the easiest time adjusting to the lack of haptic feedback and small field of view as a result of their familiarity with synthetic gaming environments. This illustrates the importance of trying to recreate a realistic environment for testing



(a) arrowhead (b) zero fpm reference line



(c) altitude cue (d) horizontal position

Figure 7-3: VAVI Design Recommendations

of displays with domain experts. Non-PC simulators that are used for training and logging hours provide a higher level of realistic visual cues and flight dynamics which PC simulators cannot provide. Some of the instabilities observed in the PC simulator version of the Harrier appear to be unique to the Microsoft PC flight simulator used in this experiment. Therefore, future experiments to test the effectiveness of the VAVI should focus on using non-PC, high-fidelity simulators such as those that are used to train helicopter and V/STOL pilots.

Chapter 8

Conclusions

There is an increasing requirement for precision vertical landing capability for air and spacecraft, which is driven by the advantages of vertical takeoff and landing capability and improvements in sensor and control technology. Pilots of vertical landing vehicles face numerous control challenges which often involve the loss of outside visual perceptual cues or the control of flight parameters within tight constraints. The challenging conditions that accompany vertical flight, in particular the hovering and landing aspects of vertical flight, place high cognitive demands on pilots. Current flight instrument displays, which are important for mitigating these challenges, still have high cognitive demand and lack perceptual decision aids specifically for hovering and landing tasks. Therefore this research was motivated by the desire to reduce the mental workload and improve performance of precision vertical operations of air and spacecraft.

The design and testing of the Vertical Altitude and Velocity Indicator demonstrates the possibility for improved mitigation of the challenges which often accompany vertical flight. Most importantly, the VAVI may improve the safety of vertical landings and hovering, while also creating cognitive reserves which can be applied to the mission rather than the control of the aircraft. Likewise, NASA has plans to return to the Moon and land with higher precision than ever before, but experimental results show that this may not be possible without an ecological perceptual aid for the astronauts.

8.1 Research Objectives and Findings

The objectives of this research were to investigate the cognitive processes of pilots and astronauts during a vertical landing, develop a vertical precision landing aid, and evaluate the effectiveness of the landing aid. The goal was to address these objectives through the following methods:

- Conduct a cognitive task analysis and develop a cognitive model for vertical landing and hover operations to establish design requirements for vertical landing instruments (see Chapter 3).
- Design an integrated flight instrument display component that addresses the design requirements and follows proven design principles (see Chapter 4).
- Use human-performance experimentation to evaluate the effectiveness of the new vertical precision landing aid on hover and vertical landing performance (see Chapters 5-7).

The cognitive model for vertical landing and hover operations in Chapter 3 illustrated the numerous mentally demanding steps required to proceed through the levels of situation awareness and act accordingly. Chapter 4 depicted the reduction in cognitive processes associated with use of the VAVI by enabling direct perception-action. The proposed cognitive model was then supported through the human participant experimentation of the VAVI which indicated improved performance and a reduction in workload as a result of the removal of unnecessary cognitive processing steps.

The VAVI design and subsequent human-performance testing resulted in some very positive findings which establish that the VAVI does in fact improve hover and landing performance and reduces mental workload. The statistically significant difference between flight displays for precise vertical speed control indicated that the VAVI improves both dynamic and static vertical speed control. Other marginally statistically significant landing performance metrics illustrate that the VAVI aids with more "smooth" control of vertical speed during landing by enabling direct-perception action of the current vehicle state and provides more consistent situation awareness of changing vehicle limits, large deviations from intended states, and possible constraint violations. Hover performance metrics, while not statistically significant at the α=0.05 level, also illustrate a trend of better performance with use of the VAVI. Workload results indicate a marginally significant reduction in workload with use of the VAVI, which is more significant among expert users.

The most revealing result of the experiment, despite the lack of statistical significance at the $\alpha = 0.5$ level, is the consistency with which the VAVI corresponds to better performance (as a function of mean, median, and standard deviation) across all test scenarios for *every* dependent measure (as illustrated in Figure 7-2 in Chapter 7). In addition, the results for the expert participants who most closely model the pilots expected to use the VAVI, illustrate a consistent and effective increase in precise landing performance across all tasks. While the results do not all show statistical significance, a positive trend would likely improve with additional testing.

8.2 Recommendations and Future Work

Though the results of this thesis indicate that the VAVI shows potential for improved performance and reduced mental workload for precision vertical landings, further investigation is warranted. The following are recommendations for future follow-on work based on the research presented in this thesis.

- The VAVI was designed to be used specifically during vertical descent or hover operations. Therefore, the VAVI should be displayed only when certain vehicle requirements are met, which indicate that a vertical descent or hover is about to be executed. The VAVI should appear to the pilot when it is most appropriate, and not during straight and level flight. Further investigation into the appropriate logic for introduction of the VAVI (fading in and out, etc.) during flight should be conducted.

- To gain a more detailed understanding of how the VAVI is being used by pilots, similar testing with use of an eye-tracking system could be performed. Specifically of interest is the application of the left, symmetric VAVI arm and relative versus precise parameter monitoring.

- The design recommendations outlined in section 7.6.1 that resulted from subjective participant responses should be further investigated and addressed.
- Testing of the VAVI in a high-fidelity V/STOL or helicopter simulator is required to determine its effectiveness in a more realistic flight setting.

The VAVI should be integrated into an already existing display to replace vertical speed and radar altitude information. The displays utilized for experimentation in this thesis were modeled after a typical V/STOL head-up display. However, specific integration and placement of the VAVI will be aircraft dependent. Specific aircraft requirements should be taken into consideration in any future design and testing of the VAVI.

Appendix A

Microsoft Flight Simulator 2004 Settings

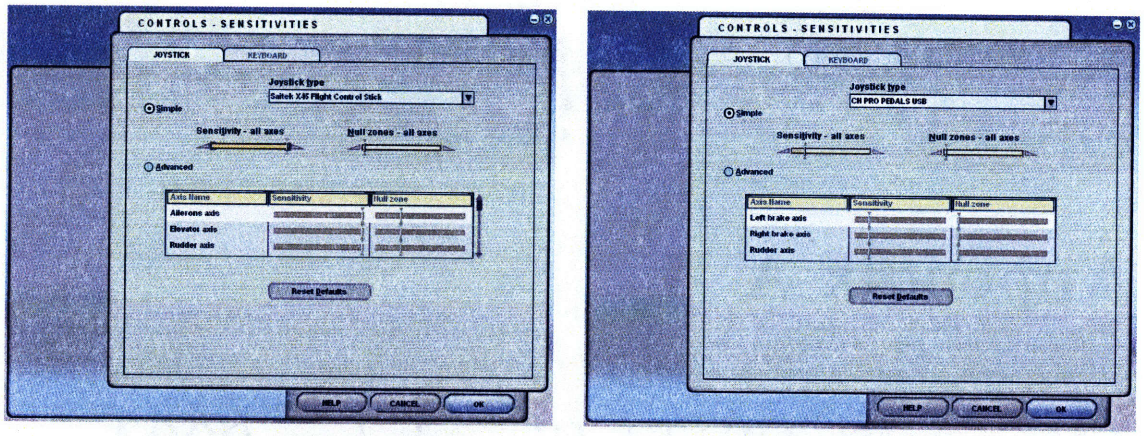
This appendix outlines the control sensitivities and realism settings of Microsoft Flight Simulator 2004 (MSFS) that were applied in the human performance experimentation of the VAVI. These settings are used to make the control of an aircraft in MSFS as realistic as possible.

A.1 Control Sensitivities

The control sensitivity settings determine the feedback of the flight controls. Figure A-1 illustrates a screenshot of the control device sensitivity settings. The pedal sensitivity was set low due to inherent over-sensitivity of the pedals. The joystick was sensitivity was set high to be as realistic as possible. The null zones for both devices were zero to remove any dead space in the control movements.

A.2 Realism

MSFS realism settings control the flight model used in the simulation. Figure A-2 illustrates a screenshot of the realism settings used for this flight simulator experiment. All levels of realism were set to average in order to provide a challenging yet acceptable



Joystick type: Saitek X45 Flight Control Stick

● Simple

○ Advanced

Joystick type: CH PRO PEDALS USB

● Simple

○ Advanced

(a) Joystick Sensitivity (b) Pedals Sensitivity

Figure A-1: Control Sensitivities

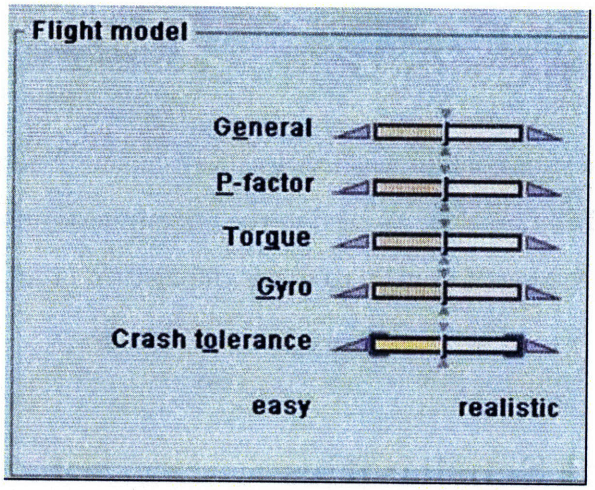


Figure A-2: Microsoft Flight Simulator Realism Settings

level of difficulty for the participants. These realism settings primarily addressed the ease of takeoff and straight and level flight which was not of interest in this experiment.

Appendix B

Consent to Participate

The following consent to participate was signed by all participants prior to taking part in the human performance experiment.

CONSENT TO PARTICIPATE IN NON-BIOMEDICAL RESEARCH

An Ecological Perceptual Aid for Lunar and Earth-Based Vertical Precision Landing

You are asked to participate in a research study conducted by Cristin Smith, from the Aeronautics and Astronautics Department at the Massachusetts Institute of Technology (M.I.T.) The results of this study will be contributed to a graduate thesis. You were selected as a possible participant in this study because you either have flight experience or flight simulator (PC-based) experience. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

• PARTICIPATION AND WITHDRAWAL

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

• PURPOSE OF THE STUDY

The purpose of this study is to investigate the effectiveness of a combined vertical speed and altitude indicator for hover aircraft vertical descents to landing. It is of interest to determine if human performance, in terms of safe and effective operations, improves with the use of this display element.

• PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

- Participate in a training session to become familiar with a Microsoft Flight Simulator Harrier platform and the corresponding control devices such as a joystick and collective
- Practice using the simulator will continue until you demonstrate an ability to perform certain flight tasks such as straight and level flight, hovering, and landing
- Execute test sessions
- Attend a debriefing to determine your subjective responses to the use of the vertical altitude and velocity indicator
- All testing will take place in a regular MIT classroom setting or at Draper Laboratory located at One Kendal Square
- Total time = less than 3 hours

• POTENTIAL RISKS AND DISCOMFORTS

There are no anticipated physical or psychological risks in this study.

• POTENTIAL BENEFITS

While there is no immediate foreseeable benefit to you as a participant in this study, your effort will provide critical insight into the effectiveness of the vertical altitude and velocity indicator (VAVI) in providing an ecological perceptual aid for pilot performance during cognitively challenging and unstable hover and vertical descent operations.

- **PAYMENT FOR PARTICIPATION**

Your participation is purely on a volunteer basis, thus no payment will be given for your participation.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. You will be assigned a subject number which will be used on all related documents to include databases, summaries of results, etc. Only one master list of subject names and numbers will exist that will remain only in the custody of Professor Cummings.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact:

Missy Cummings (Principal Investigator)
missyc@mit.edu
(617) 252-1512

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of the investigator. Further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 1-617-253 2822.

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E32-335, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Subject

____
Name of Legal Representative (if applicable)

____________________________________ ____________
Signature of Subject or Legal Representative Date

SIGNATURE OF INVESTIGATOR

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

____________________________________ ____________
Signature of Investigator Date

Appendix C

Demographic Survey

SUBJECT: ____________
DATE: ____________
TIME: ____________

An Ecological Perceptual Aid for Lunar and Earth-Based Vertical Precision Landing

Demographic Survey

1. **Age:**
   - ☐ < 21
   - ☐ 21 - 40
   - ☐ 40 - 60
   - ☐ 60 +

2. **Gender:** ☐ Male ☐ Female

3. **Occupation:**________________

4. **Do you have experience flying fixed-wing or rotary aircraft?** ☐ Yes ☐ No

If yes:

a) *Type:*

- ☐ Rotary Aircraft
- ☐ Fixed-Wing Aircraft
- ☐ Other: _________

b) *Number of hours:* ________________

5. **Do you have experience flying PC-based aircraft simulators?** ☐ Yes ☐ No

If yes:

a) *Software Package:* ________________________

b) *Total number of simulator hours:*__________________

c) *Which aircraft platform do you primarily fly?*

- ☐ Rotary Aircraft
- ☐ Fixed-Wing Aircraft
- ☐ Other: _________

d) *How often do you fly the simulator?*

- ☐ Less than 1 hour per week
- ☐ Between 1 and 4 hours per week
- ☐ Between 1 and 2 hours per day
- ☐ More than 2 hours per day

6. **Do you have experience flying a *non* PC-based aircraft simulator?** ☐ Yes ☐ No

If yes:

a) *Aircraft Platform:* ________________________

b) *Total number of simulator hours:*__________________

c) *How often do you fly the simulator?*

- ☐ 1-10 hours per 6 months
- ☐ < 1 hour per 6 months
- ☐ > 10 hours per 6 months

7. **How often do you play other video games?**

- ☐ Never
- ☐ Less than 1 hour per week
- ☐ Between 1 and 4 hours per week
- ☐ Between 1 and 2 hours per day
- ☐ More than 2 hours per day

8. **Are you color blind?** ☐ Yes ☐ No

If yes:

a) *Type:*

- ☐ Red/Green
- ☐ Blue/Yellow
- ☐ Fully
- ☐ Other: _________

Appendix D

Experiment Powerpoint Tutorial

D.1 VAVI HUD Tutorial

The following experiment tuturial was seen by participants in the VAVI HUD flight display group.

HAL

Massachusetts Institute of Technology

Experiment Tutorial

Please click to continue

DBC

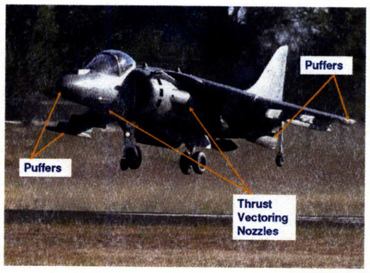
Experiment Explanation

Thank you very much for participating in this experiment. Today you will be tasked with flying an AV-8B Harrier simulator using Microsoft Flight Simulator 2004. You will be asked to takeoff, fly the Harrier, hover, and land at various locations around the country. Your participation in this experiment will help with the testing of a precision landing instrument to be used on hover aircraft and/or spacecraft such as a lunar lander.

You will be using a joystick and throttle control that simulates the thrust, and pitch and roll of a real harrier. You will have some time to train and practice flying the harrier before moving on to four short test scenarios. In order to move on to the test scenarios, you must demonstrate a certain level of proficiency during the training session. Do not be concerned about not being able to reach this level of proficiency. It is merely a way to remove some of the bias associated with using subjects of all different levels of experience. You will have 30 minutes of training available to reach this proficiency level and the majority of you will have no problem achieving this.

The following slides cover some basics about flying an AV-8B Harrier. Please take the time to read through the information thoroughly.

The Boeing/BAe AV-8B Harrier II is Short Takeoff and Vertical Landing (STOVL) single-seat multi-role attack aircraft. Several Marine squadrons have been equipped with the AV-8B.



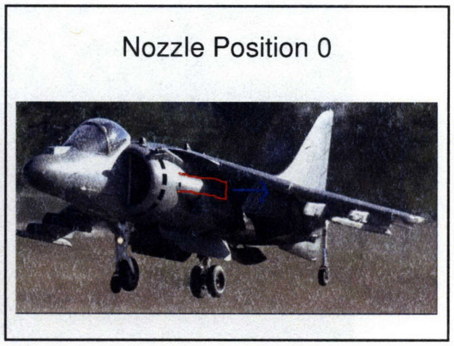
Thrust Vectoring Nozzles

- In a Harrier, vectored thrust is used to fly at low speeds
- The jet exhaust of the engine is directed downward via rotating nozzles so that thrust counters gravity
- There are 10 nozzle positions
  - **Position 0:** Nozzles directed backward (for normal flight)
  - **Position 9:** Nozzles directed downward (for vectored-thrust flight)
- "Puffers" take in air that is bled from the engine and are used to keep the aircraft level

1

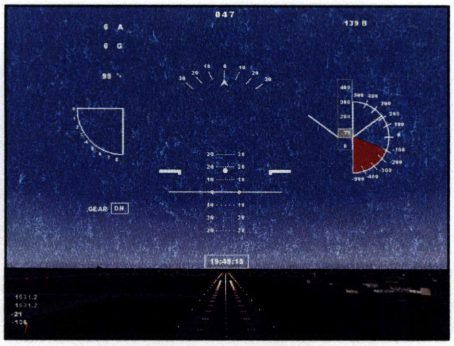
Nozzle Position 9

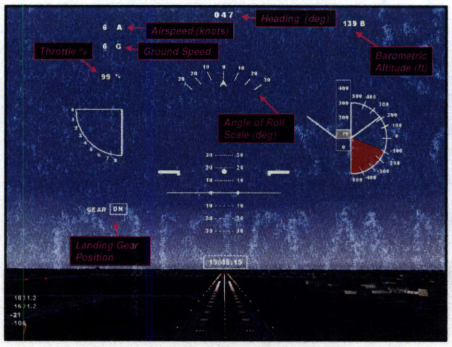
Nozzle Position 0

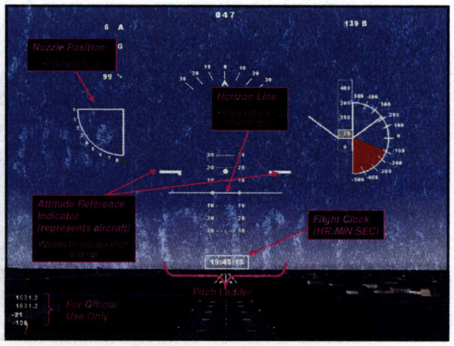


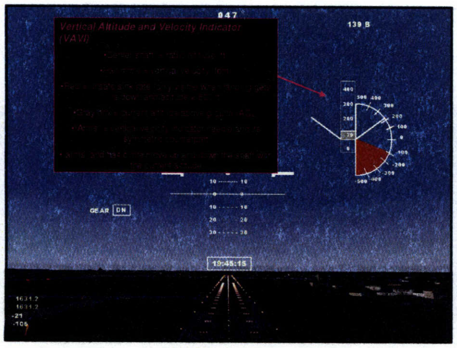
Display Description

In the following slides you will see screenshots of the Boeing/BAe AV-8B Harrier Head-Up Display (HUD) that was created for this experiment. The HUD that you will use to fly the Harrier includes typical HUD symbology with the exception of altitude and vertical speed. Altitude and vertical speed are indicated using the "VAVI" (Vertical Altitude and Velocity Indicator). The following screen shots will explain all of the symbology, including the VAVI.

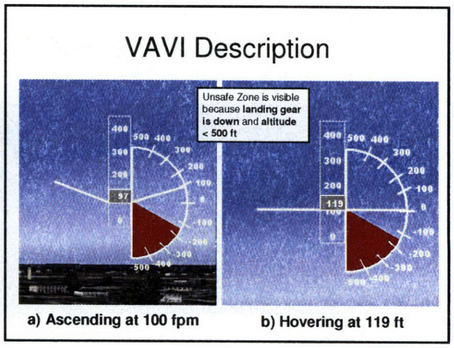








Vertical Altitude and Velocity Indicator (VAVI)

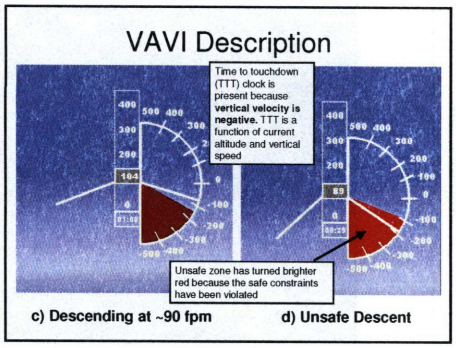


VAVI Description

Unsafe Zone is visible because **landing gear is down** and **altitude < 500 ft**

a) Ascending at 100 fpm

b) Hovering at 119 ft



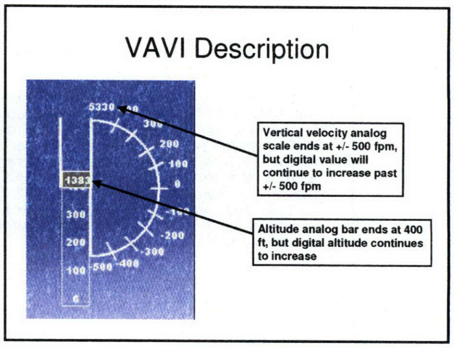
VAVI Description

Time to touchdown (TTT) clock is present because **vertical velocity is negative.** TTT is a function of current altitude and vertical speed

Unsafe zone has turned brighter red because the safe constraints have been violated

c) Descending at ~90 fpm

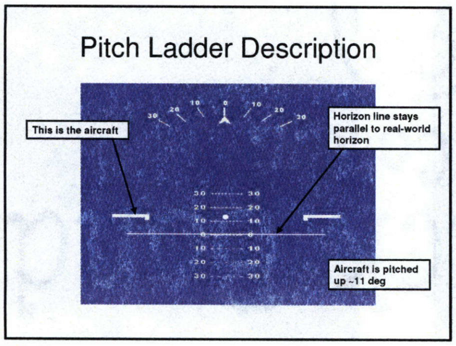
d) Unsafe Descent



VAVI Description

Vertical velocity analog scale ends at +/- 500 fpm, but digital value will continue to increase past +/- 500 fpm

Altitude analog bar ends at 400 ft, but digital altitude continues to increase

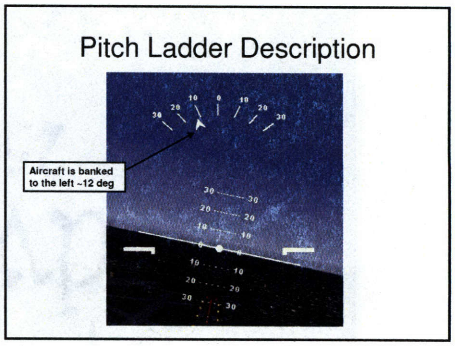


Pitch Ladder Description

This is the aircraft

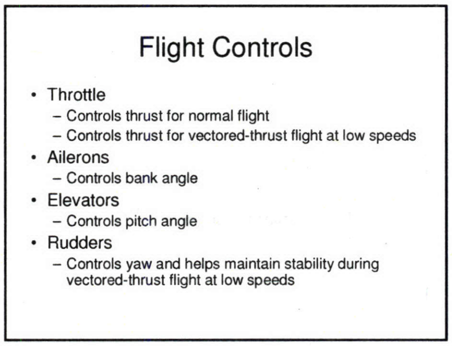
Horizon line stays parallel to real-world horizon

Aircraft is pitched up ~11 deg



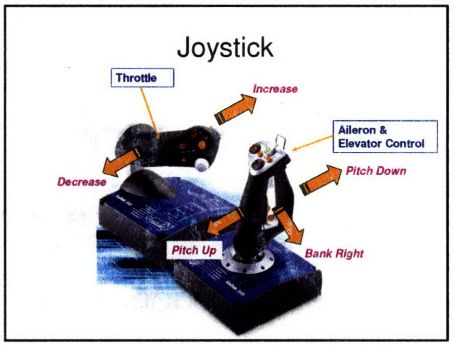
Pitch Ladder Description

Aircraft is banked to the left ~12 deg

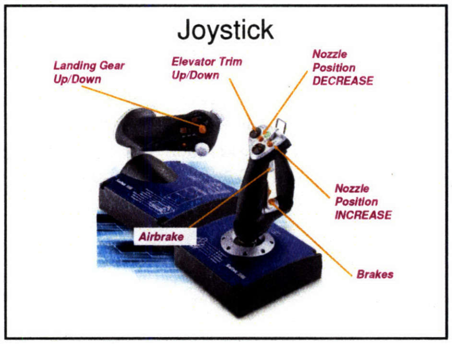


Flight Controls

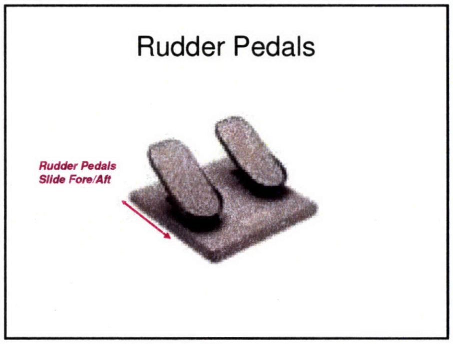
- Throttle
  - Controls thrust for normal flight
  - Controls thrust for vectored-thrust flight at low speeds
- Ailerons
  - Controls bank angle
- Elevators
  - Controls pitch angle
- Rudders
  - Controls yaw and helps maintain stability during vectored-thrust flight at low speeds



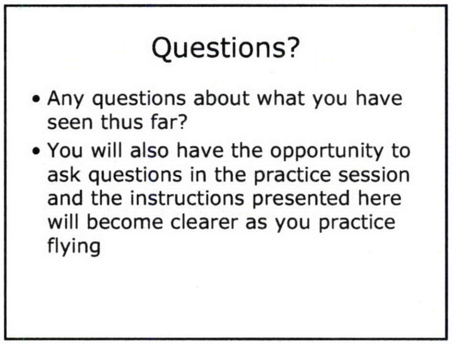
Joystick



Joystick

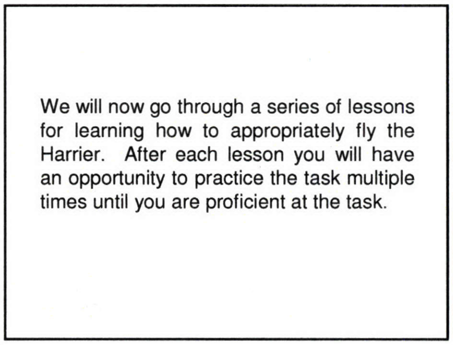


Rudder Pedals



Questions?

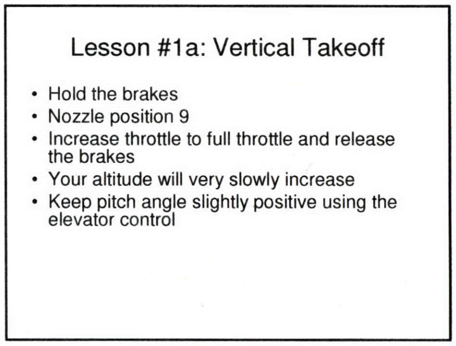
- Any questions about what you have seen thus far?
- You will also have the opportunity to ask questions in the practice session and the instructions presented here will become clearer as you practice flying



We will now go through a series of lessons for learning how to appropriately fly the Harrier. After each lesson you will have an opportunity to practice the task multiple times until you are proficient at the task.

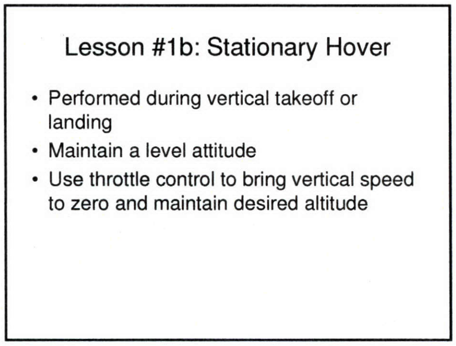
Thank you.
You are now ready to begin practicing...

GOOD LUCK!



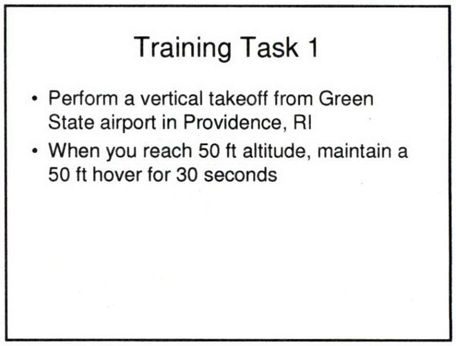
Lesson #1a: Vertical Takeoff

- Hold the brakes
- Nozzle position 9
- Increase throttle to full throttle and release the brakes
- Your altitude will very slowly increase
- Keep pitch angle slightly positive using the elevator control



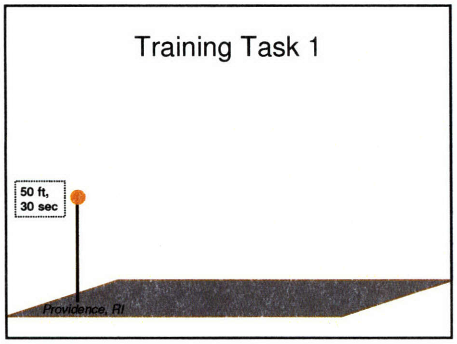
Lesson #1b: Stationary Hover

- Performed during vertical takeoff or landing
- Maintain a level attitude
- Use throttle control to bring vertical speed to zero and maintain desired altitude

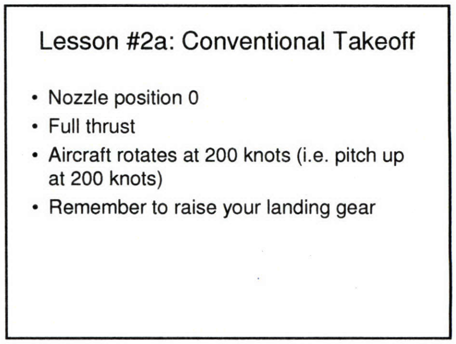


Training Task 1

- Perform a vertical takeoff from Green State airport in Providence, RI
- When you reach 50 ft altitude, maintain a 50 ft hover for 30 seconds

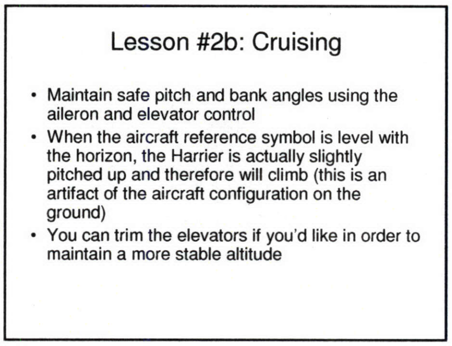


Training Task 1



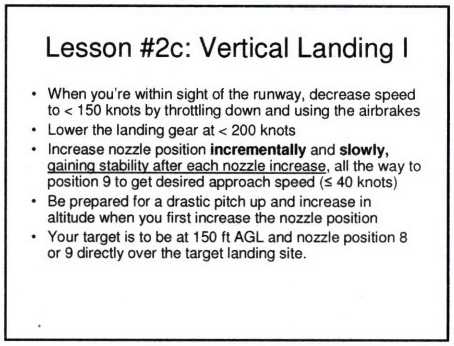
Lesson #2a: Conventional Takeoff

- Nozzle position 0
- Full thrust
- Aircraft rotates at 200 knots (i.e. pitch up at 200 knots)
- Remember to raise your landing gear



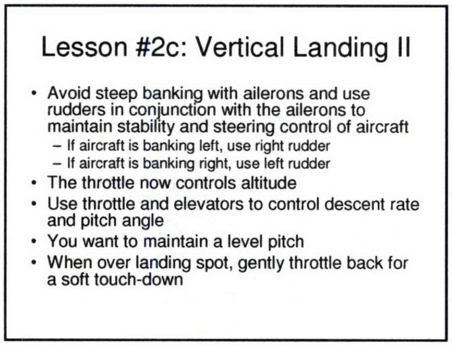
Lesson #2b: Cruising

- Maintain safe pitch and bank angles using the aileron and elevator control
- When the aircraft reference symbol is level with the horizon, the Harrier is actually slightly pitched up and therefore will climb (this is an artifact of the aircraft configuration on the ground)
- You can trim the elevators if you'd like in order to maintain a more stable altitude



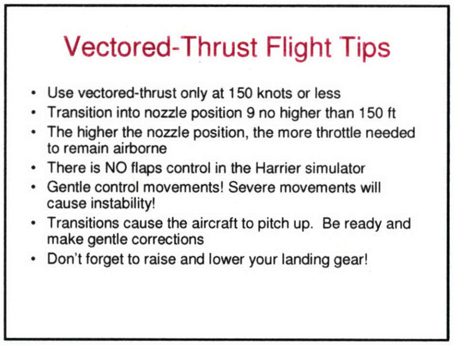
Lesson #2c: Vertical Landing I

- When you're within sight of the runway, decrease speed to < 150 knots by throttling down and using the airbrakes
- Lower the landing gear at < 200 knots
- Increase nozzle position **incrementally** and **slowly,** gaining stability after each nozzle increase, all the way to position 9 to get desired approach speed (≤ 40 knots)
- Be prepared for a drastic pitch up and increase in altitude when you first increase the nozzle position
- Your target is to be at 150 ft AGL and nozzle position 8 or 9 directly over the target landing site.



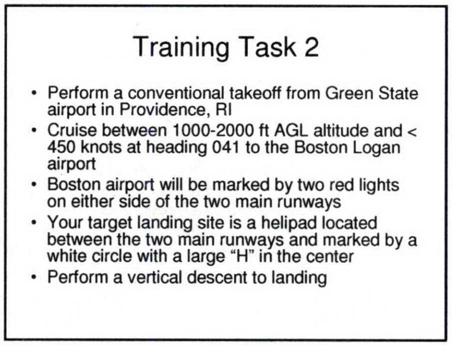
Lesson #2c: Vertical Landing II

- Avoid steep banking with ailerons and use rudders in conjunction with the ailerons to maintain stability and steering control of aircraft
  - If aircraft is banking left, use right rudder
  - If aircraft is banking right, use left rudder
- The throttle now controls altitude
- Use throttle and elevators to control descent rate and pitch angle
- You want to maintain a level pitch
- When over landing spot, gently throttle back for a soft touch-down



Vectored-Thrust Flight Tips

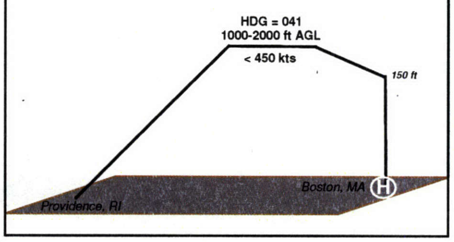
- Use vectored-thrust only at 150 knots or less
- Transition into nozzle position 9 no higher than 150 ft
- The higher the nozzle position, the more throttle needed to remain airborne
- There is NO flaps control in the Harrier simulator
- Gentle control movements! Severe movements will cause instability!
- Transitions cause the aircraft to pitch up. Be ready and make gentle corrections
- Don't forget to raise and lower your landing gear!



Training Task 2

- Perform a conventional takeoff from Green State airport in Providence, RI
- Cruise between 1000-2000 ft AGL altitude and < 450 knots at heading 041 to the Boston Logan airport
- Boston airport will be marked by two red lights on either side of the two main runways
- Your target landing site is a helipad located between the two main runways and marked by a white circle with a large "H" in the center
- Perform a vertical descent to landing

Training Task 2



Great Job! You have successfully passed the training sessions!

- Now that you have completed your training, you will participate in 2 short test scenarios
- At the completion of each test scenario, you will be asked a series of question on paper (in flow-chart form) that will assess your experience flying

---

Flight Objectives (1)

- The following tasks are the **key goals** of this experiment and should be performed to the best of your ability. They are in no specific order
- Primary Goals:
  - Land at the target landing site
  - Capture the commanded hover altitude as precisely as possible
  - Maintain an *accurate* commanded hover altitude
  - Maintain an *accurate* commanded sink rate
- Secondary Goal:
  - Minimize horizontal movement during a vertical descent

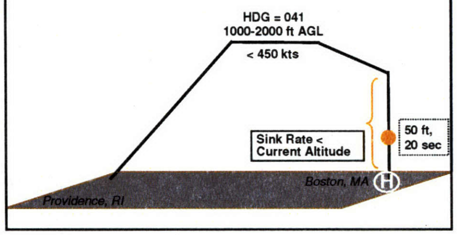
Flight Objectives (2)

- The following tasks are **NOT of importance** in this experiment
  - Takeoff
  - Straight and level flight

Test Scenario #1

- Perform a conventional takeoff from Providence
- Maintain a heading of 041 at 1000 – 2000 ft radar altitude and < 450 knots to the Boston airport
- Slow to a **hover** at **50 feet** altitude above the helipad or **when you stable out** and maintain the hover for **20 seconds.** Please tell me when you are starting your hover and do not try to climb back up to the hover altitude if you miss it.
- Perform a vertical landing to the helipad while maintaining a dynamic **sink rate less than your current altitude** (i.e. if you're at 150 feet, don't descend any faster than 150 fpm, etc.)

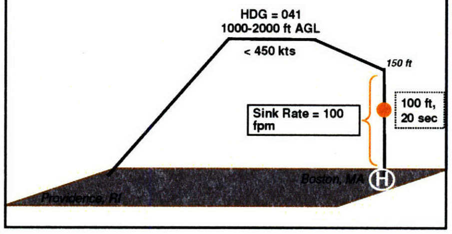
Test Scenario #1



Test Scenario #2

- Perform a conventional takeoff from Providence
- Maintain a heading of 041 at 1000 – 2000 ft radar altitude and < 450 knots to the Boston airport
- Slow to a **hover** at **100 feet** altitude above the helipad or **when you stable out** and maintain the hover for **20 seconds.** Please tell me when you are starting your hover and do not try to climb back up to the hover altitude if you miss it.
- Perform a vertical landing to the helipad while maintaining a constant **sink rate = 100 fpm**

Test Scenario #2



D.2 Conventional HUD Tutorial

The following experiment tuturial was seen by participants in the Conventional HUD flight display group.

HAL

Massachusetts
Institute of
Technology

Experiment Tutorial

DBC

Please click to continue

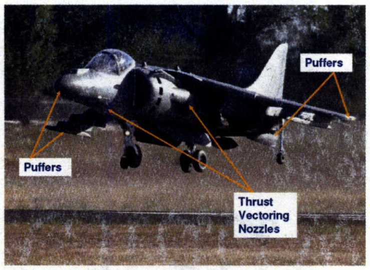
Experiment Explanation

Thank you very much for participating in this experiment. Today you will be tasked with flying an AV-8B Harrier simulator using Microsoft Flight Simulator 2004. You will be asked to takeoff, fly the Harrier, hover, and land at various locations around the country. Your participation in this experiment will help with the testing of a precision landing instrument to be used on hover aircraft and/or spacecraft such as a lunar lander.

You will be using a joystick and throttle control that simulates the thrust, and pitch and roll of a real harrier. You will have some time to train and practice flying the harrier before moving on to four short test scenarios. In order to move on to the test scenarios, you must demonstrate a certain level of proficiency during the training session. Do not be concerned about not being able to reach this level of proficiency. It is merely a way to remove some of the bias associated with using subjects of all different levels of experience. You will have 30 minutes of training available to reach this proficiency level and the majority of you will have no problem achieving this.

The following slides cover some basics about flying an AV-8B Harrier. Please take the time to read through the information thoroughly.

The Boeing/BAe AV-8B Harrier II is Short Takeoff and Vertical Landing (STOVL) single-seat multi-role attack aircraft. Several Marine squadrons have been equipped with the AV-8B.

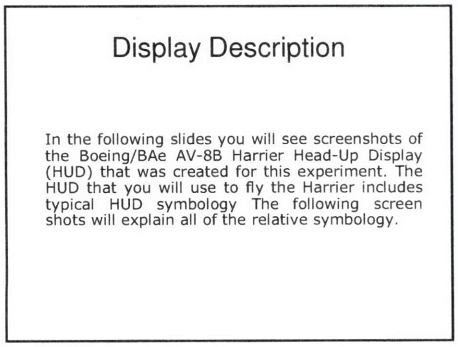


Thrust Vectoring Nozzles

- In a Harrier, vectored thrust is used to fly at low speeds
- The jet exhaust of the engine is directed downward via rotating nozzles so that thrust counters gravity
- There are 10 nozzle positions
  - **Position 0:** Nozzles directed backward (for normal flight)
  - **Position 9:** Nozzles directed downward (for vectored-thrust flight)
- "Puffers" take in air that is bled from the engine and are used to keep the aircraft level

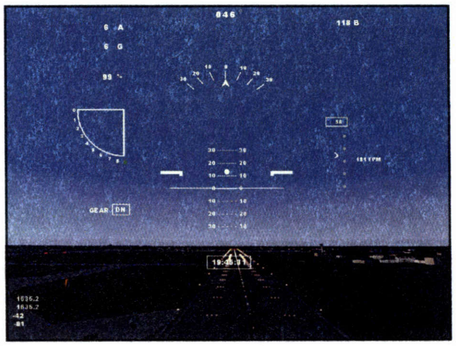
Nozzle Position 9

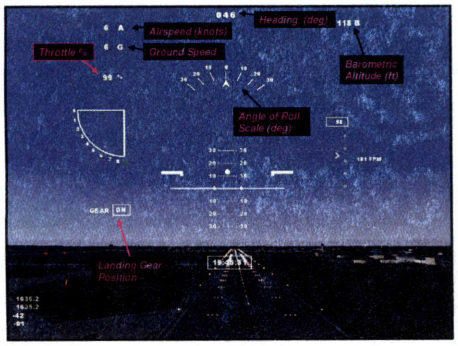
Nozzle Position 0



Display Description

In the following slides you will see screenshots of the Boeing/BAe AV-8B Harrier Head-Up Display (HUD) that was created for this experiment. The HUD that you will use to fly the Harrier includes typical HUD symbology The following screen shots will explain all of the relative symbology.





Heading (deg)

Airspeed (knots)

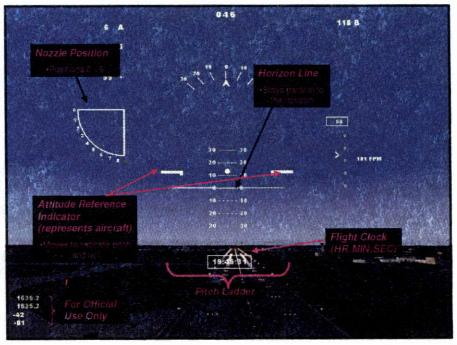
Ground Speed

Throttle %

Barometric Altitude (ft)

Angle of Roll Scale (deg)

Landing Gear Position



Nozzle Position
- Positions 0 - 8

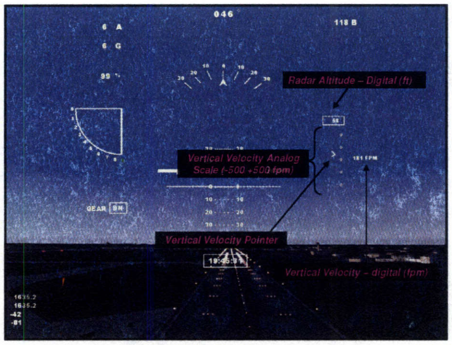
Horizon Line
- Stays parallel to the horizon

Attitude Reference Indicator (represents aircraft)
- Moves to indicate pitch and roll

Flight Clock (HR.MIN.SEC)

Pitch Ladder

For Official Use Only

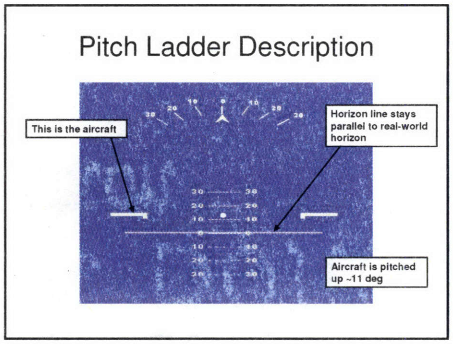


Radar Altitude – Digital (ft)

Vertical Velocity Analog Scale (-500 +500 fpm)

Vertical Velocity Pointer

Vertical Velocity – digital (fpm)

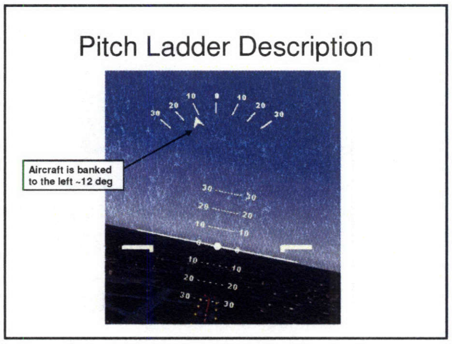


Pitch Ladder Description

This is the aircraft

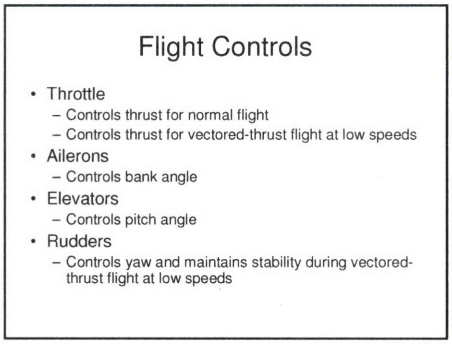
Horizon line stays parallel to real-world horizon

Aircraft is pitched up ~11 deg



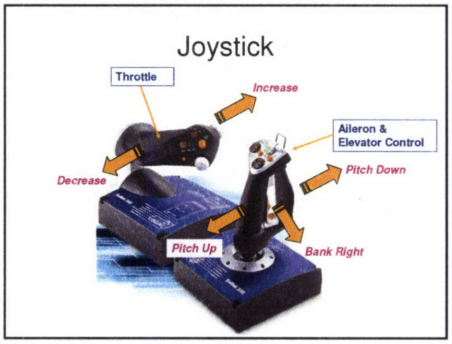
Pitch Ladder Description

Aircraft is banked to the left ~12 deg



Flight Controls

- Throttle
  - Controls thrust for normal flight
  - Controls thrust for vectored-thrust flight at low speeds
- Ailerons
  - Controls bank angle
- Elevators
  - Controls pitch angle
- Rudders
  - Controls yaw and maintains stability during vectored-thrust flight at low speeds



Joystick

Throttle

Increase

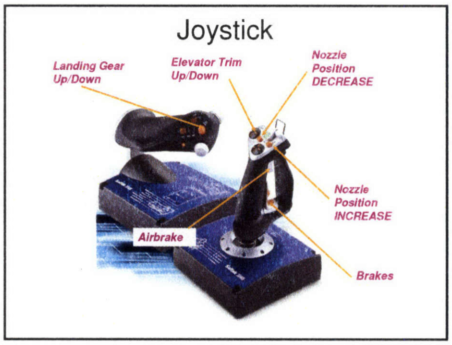
Decrease

Aileron & Elevator Control

Pitch Down

Pitch Up

Bank Right



Joystick

Landing Gear Up/Down

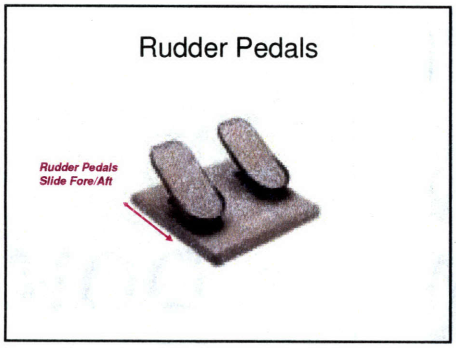
Elevator Trim Up/Down

Nozzle Position DECREASE

Nozzle Position INCREASE

Airbrake

Brakes



Rudder Pedals

Questions?

- Any questions about what you have seen thus far?
- You will also have the opportunity to ask questions in the practice session and the instructions presented here will become clearer as you practice flying

We will now go through a series of lessons for learning how to appropriately fly the Harrier. After each lesson you will have an opportunity to practice the task multiple times until you are proficient at the task.

HAL

Thank you.
You are now ready to begin practicing...

GOOD LUCK!

Lesson #1a: Vertical Takeoff

- Hold the brakes
- Nozzle position 9
- Increase throttle to full throttle and release the brakes
- Your altitude will very slowly increase
- Keep pitch angle slightly positive using the elevator control

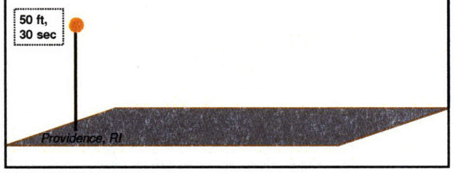
Lesson #1b: Stationary Hover

- Performed during vertical takeoff or landing
- Maintain a level attitude
- Use throttle control to bring vertical speed to zero and maintain desired altitude

Training Task 1

- Perform a vertical takeoff from Green State airport in Providence, RI
- When you reach 50 ft altitude, maintain a 50 ft hover for 30 seconds

Training Task 1



Lesson #2a: Conventional Takeoff

- Nozzle position 0
- Full thrust
- Aircraft rotates at 200 knots (i.e. pitch up at 200 knots)
- Remember to raise your landing gear

Lesson #2b: Cruising

- Maintain safe pitch and bank angles using the aileron and elevator control
- When the aircraft reference symbol is level with the horizon, the Harrier is actually slightly pitched up and therefore will climb (this is an artifact of the aircraft configuration on the ground)
- You can trim the elevators if you'd like in order to maintain a more stable altitude

Lesson #2c: Vertical Landing I

- When you're within sight of the runway, decrease speed to < 150 knots by throttling down and using the airbrakes
- Lower the landing gear at < 200 knots
- Increase nozzle position **incrementally** and **slowly,** <u>gaining stability after each nozzle increase</u>, all the way to position 9 to get desired approach speed (≤ 40 knots)
- Be prepared for a drastic pitch up and increase in altitude when you first increase the nozzle position
- Your target is to be at 150 ft AGL and nozzle position 8 or 9 directly over the target landing site.

Lesson #2c: Vertical Landing II

- Avoid steep banking with ailerons and use rudders in conjunction with the ailerons to maintain stability and steering control of aircraft
    - If aircraft is banking left, use right rudder
    - If aircraft is banking right, use left rudder
- The throttle now controls altitude
- Use throttle and elevators to control descent rate and pitch angle
- You want to maintain a level pitch
- When over landing spot, gently throttle back for a soft touch-down

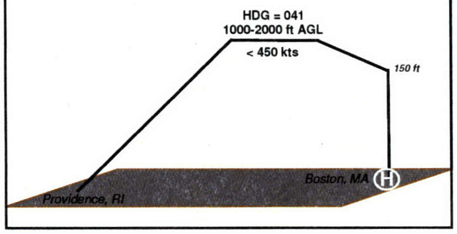
Vectored-Thrust Flight Tips

- Use vectored-thrust only at 150 knots or less
- Transition into nozzle position 9 no higher than 150 ft
- The higher the nozzle position, the more throttle needed to remain airborne
- There is NO flaps control in the Harrier simulator
- Gentle control movements! Severe movements will cause instability!
- Transitions cause the aircraft to pitch up. Be ready and make gentle corrections
- Don't forget to raise and lower your landing gear!

Training Task 2

- Perform a conventional takeoff from Green State airport in Providence, RI
- Cruise between 1000-2000 ft AGL altitude and < 450 knots at heading 041 to the Boston Logan airport
- Boston airport will be marked by two red lights on either side of the two main runways
- Your target landing site is a helipad located between the two main runways and marked by a white circle with a large "H" in the center
- Perform a vertical descent to landing

Training Task 2



Great Job! You have successfully passed the training sessions!

- Now that you have completed your training, you will participate in 2 short test scenarios
- At the completion of each test scenario, you will be asked a series of question on paper (in flow-chart form) that will assess your experience flying

Flight Objectives (1)

- The following tasks are the **key goals** of this experiment and should be performed to the best of your ability. They are in no specific order
- Primary Goals:
  - Land at the target landing site
  - Capture the commanded hover altitude as precisely as possible
  - Maintain an *accurate* commanded hover altitude
  - Maintain an *accurate* commanded sink rate
- Secondary Goal:
  - Minimize horizontal movement during a vertical descent

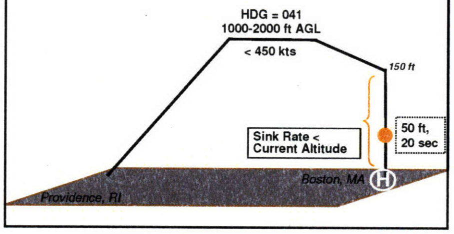
Flight Objectives (2)

- The following tasks are **NOT of importance** in this experiment
  - Takeoff
  - Straight and level flight

Test Scenario #1

- Perform a conventional takeoff from Providence
- Maintain a heading of 041 at 1000 – 2000 ft radar altitude and < 450 knots to the Boston airport
- Slow to a **hover** at **50 feet** altitude above the helipad or **when you stable out** and maintain the hover for **20 seconds.** Please tell me when you are starting your hover and do not try to climb back up to the hover altitude if you miss it.
- Perform a vertical landing to the helipad while maintaining a dynamic **sink rate less than your current altitude** (i.e. if you're at 150 feet, don't descend any faster than 150 fpm, etc.)

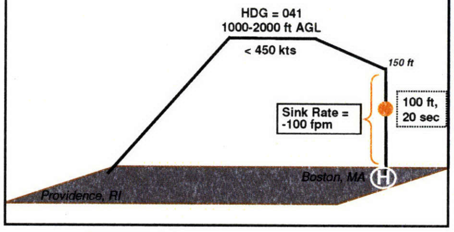
Test Scenario #1


HDG = 041
1000-2000 ft AGL
< 450 kts
150 ft
Sink Rate <
Current Altitude
50 ft,
20 sec
Providence, RI
Boston, MA

Test Scenario #2

- Perform a conventional takeoff from Providence
- Maintain a heading of 041 at 1000 – 2000 ft radar altitude and < 450 knots to the Boston airport
- Slow to a **hover** at **100 feet** altitude above the helipad or **when you stable out** and maintain the hover for **20 seconds.** Please tell me when you are starting your hover and do not try to climb back up to the hover altitude if you miss it.
- Perform a vertical landing to the helipad while maintaining a constant **sink rate = 100 fpm**

Test Scenario #2


HDG = 041
1000-2000 ft AGL
< 450 kts
150 ft
Sink Rate =
-100 fpm
100 ft,
20 sec
Providence, RI
Boston, MA

Appendix E

Semi-Structured Interview Questions

This appendix outlines the semi-structured interview questions.

E.1 VAVI HUD Questions

The following questions were used to guide post-experiment discussion with the participants who used the VAVI HUD.

1. Did you use the VAVI? If so, how?
2. Was there anything negative or distracting about the VAVI?
3. Is there any additional information that you wished you had that you think would have helped with the vertical descent?

E.2 Conventional HUD Questions

The following questions were used to guide post-experiment discussion with the participants who used the conventional HUD.

1. What process did you go through to determine your vertical velocity and position relative to where you wanted to be?

2. Did you find these tasks difficult? If so, what was difficult about them?
3. Is there any additional information that you wished you had that you think would have helped with the vertical descent?

Appendix F

Descriptive Statistics

This appendix outlines the demographics of the particpant pool used in the human peformance experimentation.

F.1 Demographics

Table F.1: Study Demographics

Category	N	Min	Max	Mean	Std. Dev.
Age (years)	22	12	63	34	14
Rotary Wing Experience (hours)	11	15	9000	1858	2908
Fixed Wing Experience (hours)	11	4	5000	889	1492
Flight Simulator Experience (hours)	19	10	400	100	125
Student (Y/N)	6	-	-	-	-
Gender (M/F)	20M,2F	-	-	-	-

F.2 Top Performer Non-Parametric Summary

Table F.2: Top Performer Non-Parametric Summary

	Mann-Whitney			Wilcoxon	
Dep. Measure	HUD	U	z	VS Heuristic	z
Hover Accuracy	$p = 0.589$	14.00	-0.647	N/A	N/A
Hover Precision	$p = 0.126$	6.00	-1.643	N/A	N/A
VS Precision	$p = 0.015$	3.00	-2.402	$p = 0.600$	-0.524
Descent Duration Error	$p = 0.699$	15.00	-0.480	$p = 0.028$	-2.201
10-pt Workload	$p = 0.026$	4.00	-2.407	$p = 0.157$	-1.414

Appendix G

Statistical Tests

G.1 Analysis of Variance (ANOVA)

Analysis of variance tests are used to test the difference between the means of two or more groups. The groups correspond to the different levels of the independent variables. Each factor level has a probability distribution of responses. The ANOVA model makes the following assumptions about those probability distributions [51]:

1. Each probability distribution is normal.
2. Each probability distribution has the same variance.
3. The response for each factor level are random selections from the corresponding probability distribution and are independent of the responses for any other factor level.

G.1.1 Single Factor

Single factor or one-way ANOVA test the difference between groups that are classified by a single independent variable. The basic model for a one-way ANOVA is outlined in Equation G.1 where i is the factor level and j is the number of cases.

$$Y_{ij} = \mu_i + \epsilon_{ij} \tag{G.1}$$

G.1.2 Multiple Factor

Multiple factor ANOVA tests the effects of two or more factors simultaneously. Multiple factor studies are good because they parse out any interaction between the factors meaning they determine any joint effects of the two factors. Multiple factor studies are often more efficient and can strengthen the validity of the findings [51]. The basic model for a multiple factor ANOVA is outlined in Equation G.2 where i is the first factor level, j is 2nd factor level, and k is the observation from the number of cases.

$$Y_{ijk} = \mu_{ij} + \epsilon_{ijk} \tag{G.2}$$

G.2 Kolmogorov-Smirnov Test of Normality

The Kolmogorov-Smirnov (KS) test is used to determine if a sample of N data points comes from a population with a specific distribution. In the context of this study, the KS test is used to determine if samples come from a population with a normal cumulative distribution. The KS test is a very conservative test in terms of checking for normality. To use the test, a D statistic is computed in the following manner.

$$D = Max\left|F(Y_i) - \frac{i}{N}\right| \tag{G.3}$$

F is the theoretical cumulative distribution of the distribution being tested, which must be continuous and fully defined in terms of a mean and standard deviation. A comparison of this D statistic to a critical D value from a published table determines the normality of the distribution. If the D statistic is greater than the critical value, it is concluded that the distribution is not normal. Therefore, normality is shown by a non-significant results in this test. In addition to requiring that the distribution be continuous, the KS test can be more sensitive near the center of the distribution than at the tails. Despite these minor disadvantages of the test, it is a very conservative test that is powerful for determining normality of a data set.

G.3 Levene's Test of Equality of Error Variance

Levene's test is used to test if k samples have equal variances in which case there would be homogeneity of variance. The Levene test tests the null hypothesis that all variances are equal. Therefore, to show that the variances are equal, we look for non-significance in this test. The following formula (Equation G.4) is used to calculate the Levene statistic where variable Y has a sample size of N divided into k subgroups and N_i is the sample size of the ith subgroup [52].

$$W = \frac{(N-k)\sum N_i(\overline{Z_{i.}} - \overline{Z_{..}})^2}{(k-1)\sum\sum(Z_{ij} - \overline{Z_{i.}})^2} \tag{G.4}$$

G.4 Mann Whitney U Test

The Mann-Whitney U Test is a non-parametric test based on rankings for determining whether two samples come from the same population when the normality or homogeneity of variance assumptions are violated. In this test, all the sample values are ranked and the sum of the ranks for each sample is calculated and denoted by R_1 and R_2. With samples sizes N_1 and N_2, the following U statistic corresponding to sample 1 is calculated.

$$H = N_1 N_2 + \frac{N_1(N_1+1)}{2} - R_1 \tag{G.5}$$

Since the sampling distribution of U is symmetrical, the mean and variance can be defined as outlined below.

$$\mu_U = \frac{N_1 N_2}{2} \tag{G.6}$$

$$\sigma_U^2 = \frac{N_1 N_2 (N_1 + N_2 + 1)}{12} \tag{G.7}$$

From this information, a z statistic can be calculated in the following manner. If both sample sizes are eight or larger, then the U distribution is nearly normal with a mean of 0 and a variance of 1. Then, using a z table, it is possible to determine whether the two samples differ significantly.

$$z = \frac{U - \mu_U}{\sigma_U} \tag{G.8}$$

G.5 Wilcoxon Signed-Rank Test

The Wilcoxon Signed-Rank Test is a non-parametric test which is an alternative to a paired t-test for comparing the differences between measurements when normality assumptions are violated. The Wilcoxon test involves using the magnitudes and signs of the differences between paired observations to determine if there is a significant difference. The following steps are taken to determine the signed-rank of the observations [53].

1. take the absolute difference $|X_a - X_b|$ for each pair;
2. omit from consideration those cases where $|X_a - X_b|$=0;
3. rank the remaining absolute differences, from smallest to largest, employing tied ranks where appropriate;
4. assign to each such rank a "+" sign when $X_a - X_b > 0$ and a "-" sign when $X_a - X_b < 0$;
5. and then calculate the value of W for the Wilcoxon test, which is equal to the sum of the signed ranks. The number of signed ranks, here designated as $n_{s/r}$, is equal to the number of $X_a X_b$ pairs at the beginning minus the number of pairs for which $|X_a - X_b|$=0.

"When $n_{s/r}$ is equal to or greater than 10, the sampling distribution of W is a reasonably close approximation of the normal distribution" [53]. The corresponding p-value is found in an appropriate table.

Appendix H

Top Performer Evaluation

This appendix illustrates the performance of all of participants for each of the dependent variables. The top performers are circled and were determined based on their average rankings. Every participant from each flight display group was ranked and the average of those rankings across all dependent variables was used to determine the top performers. A low average ranking indicates consistent good performance. Table H.1 outlines the average rankings for all participants and highlights the top performers in each group.

Table H.1: Top Participants Average Ranking

VAVI		No VAVI	
Subject #	Avg Ranking	Subject #	Avg Ranking
3	4.13	4	7.00
6	4.88	5	4.50
10	*3.38*	11	*4.25*
15	4.75	12	4.38
20	*3.00*	14	*3.38*
21	5.67	16	4.75
23	6.33	17	*2.86*
24	6.12	29	6.60
25	4.57	30	5.13
27	*3.50*	31	4.43
28	7.50	-	-

H.1 VAVI Flight Display Group

H.1.1 Hover Performance

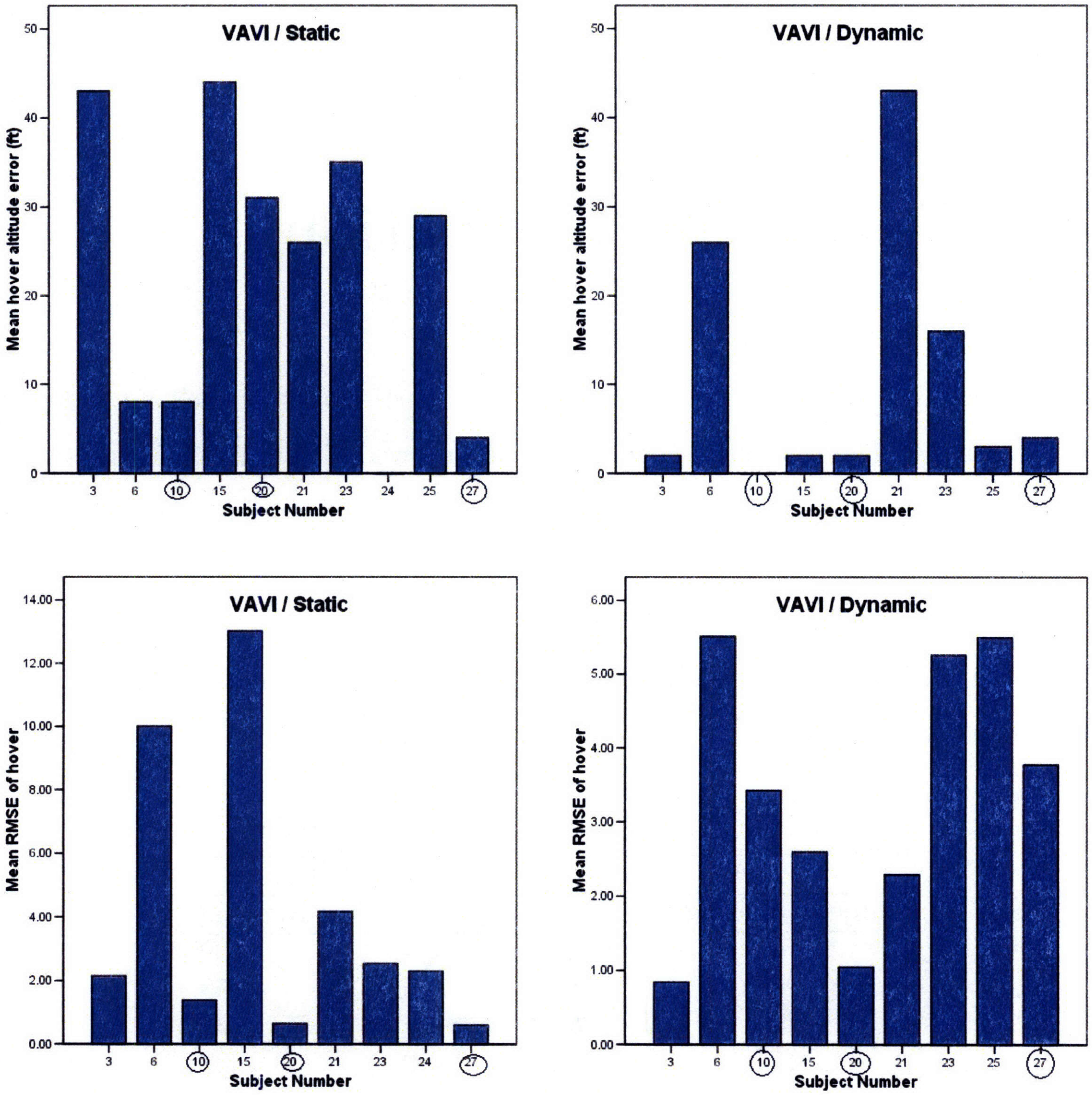


Figure H-1: Top Participants Hover Performance, VAVI Flight Display Group

H.1.2 Landing Performance

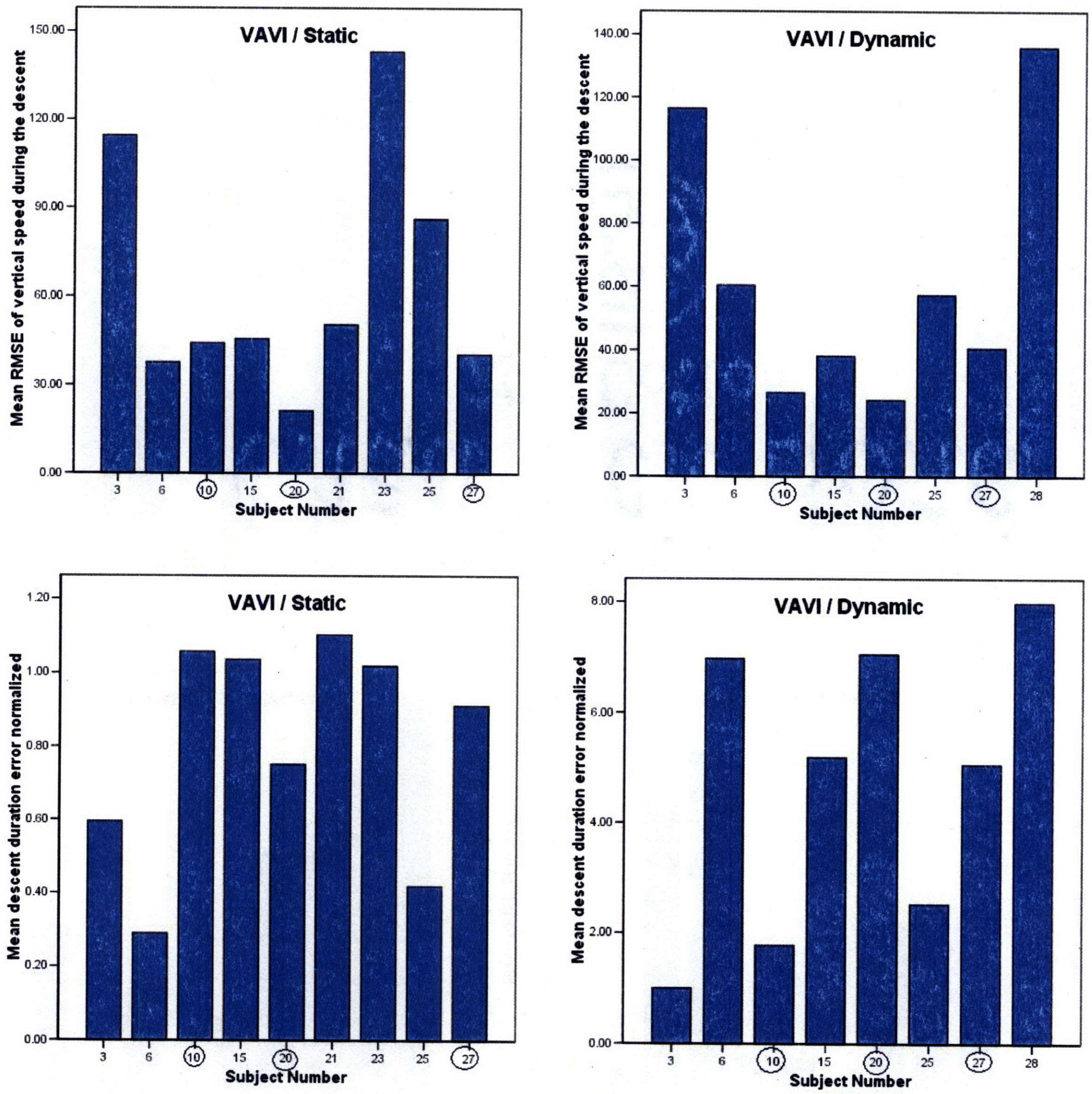


Figure H-2: Top Participants Landing Performance, VAVI Flight Display Group

H.2 Conventional Flight Display Group

H.2.1 Hover Performance

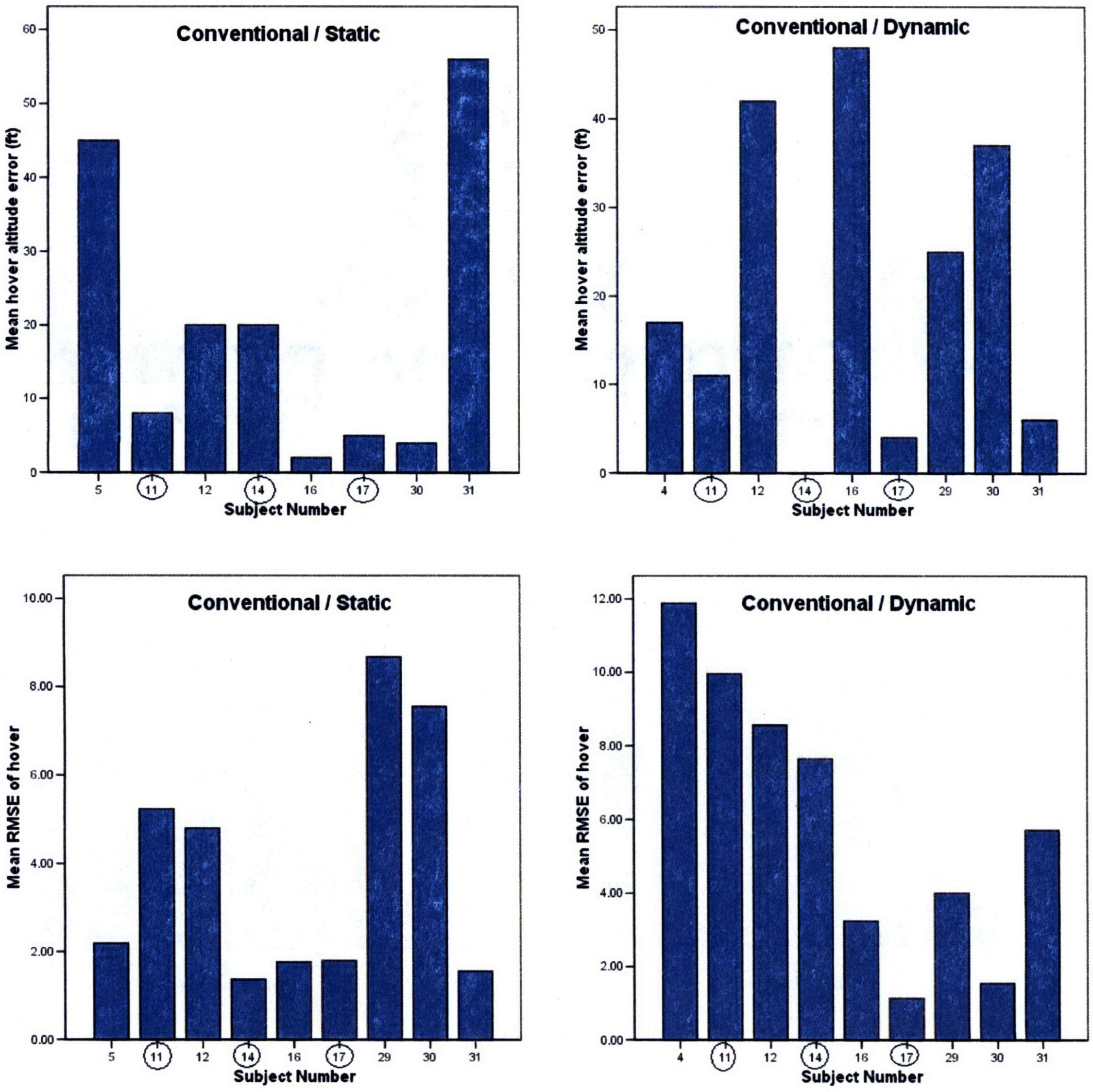


Figure H-3: Top Participants Hover Performance, Conventional Flight Display Group

H.2.2 Landing Performance

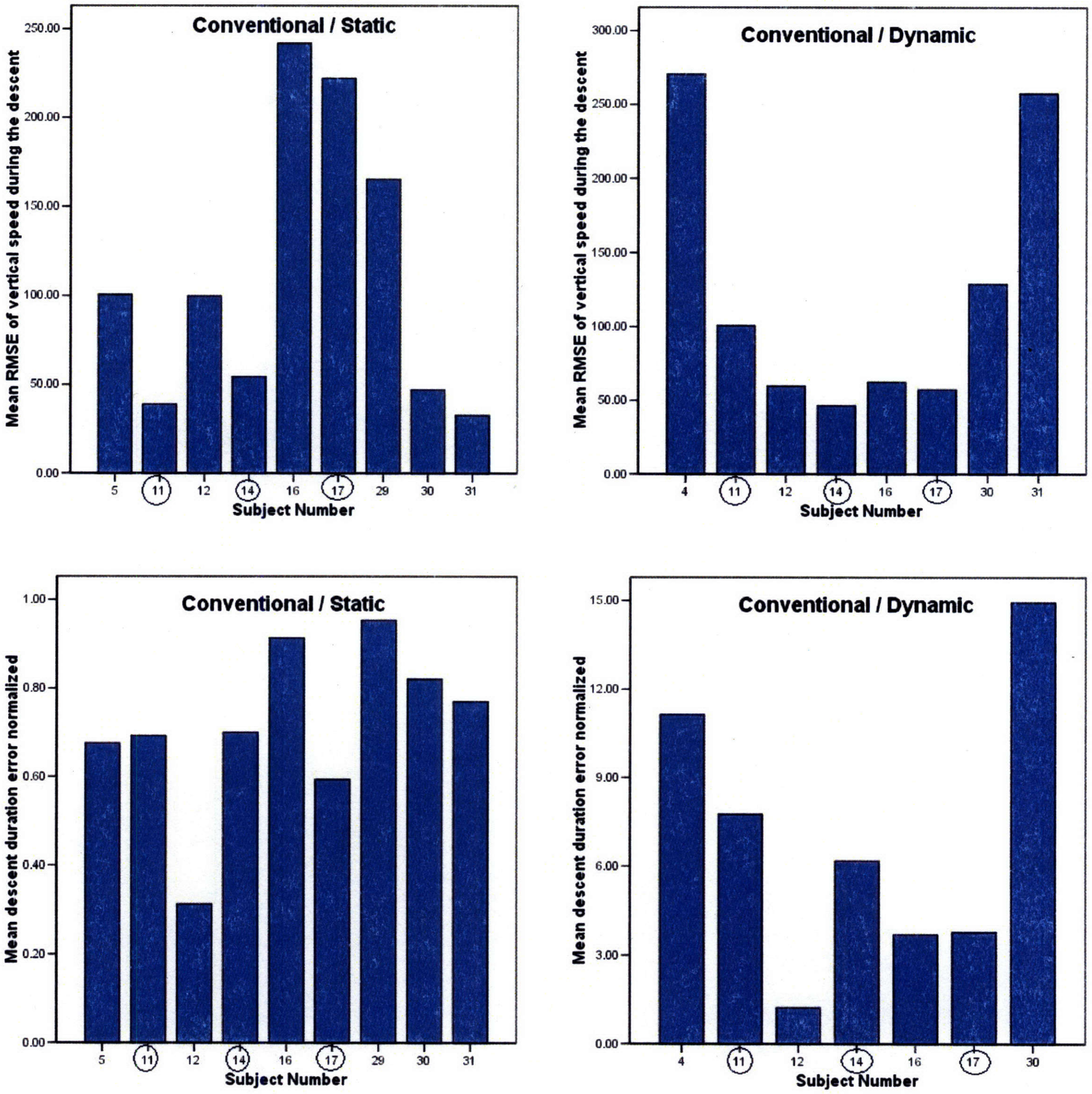


Figure H-4: Top Participants Landing Performance, Conventional Flight Display Group

Bibliography

[1] L. Fuhrman, T. Fill, L. Forest, L. Norris, S. Paschall, and Y. Tao, "A reusable design for precision lunar landing systems," in *International Lunar Conference 2005*, 2005.

[2] D. Walters, "Landing VTOL aircraft in adverse conditions and some possible solutions," in *AGARD Guidance and Control Panel, Symposium on Aircraft Landing Systems*, (Cambridge, MA), North Atlantic Treaty Organization, 1969.

[3] D. Kohlman, *Introduction to V/STOL Airplanes.* Iowa State University Press/Ames, 1981.

[4] "V/STOL displays for approach and landing," AGARD Report 594, North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development, London, Jul 1972.

[5] J. Leishman, *Principles of Helicopter Aerodynamics.* Cambridge Aerospace Series, Cambridge University Press, 2000.

[6] P. Cantrell, "All star helicopters," 2006. http://www.copters.com/.

[7] J. Franklin, M. Stortz, P. Borchers, and E. I. Moralez, "Flight evaluation of advanced controls and displays for transition and landing on the NASA V/STOL systems research aircraft," NASA Technical Paper 3607, National Aeronautics and Space Administration, 1996.

[8] "Global security," 2005. http://www.globalsecurity.org/military/systems/aircraft/b206.htm.

[9] "Settling with power," 23 Dec 2002. http://www.dynamicflight.com/aero dynamics/settling_power/.

[10] T. Lankford, *Aviation Weather Handbook.* New York: McGraw-Hill, 2001.

[11] B. Hamilton, "Helicopter human factors," in *Handbook of Aviation Human Factors* (D. Garland, J. Wise, and V. Hopkin, eds.), Mahwah, NJ: Lawrence Erlbaum Associates, Inc., 1999.

[12] F. Previc and W. Ercoline, *Spatial Disorientation in Aviation.* Progress in Astronautics and Aeronautics Series, 203, AIAA, 2004.

[13] 101st Airborne Division (Air Assault), "Operation iraqi freedom safety lessons learned," 19 Jan 2003. http://www.globalsecurity.org/military/library/report /2003/101abn-oif_safety-lessons-learned_sep03.ppt#258.

[14] M. McCarter, *Precision Landing Systems.* http://www.special-operations-technology.com/article.cfm?DocID=585: Special Operations Technology Online Archives, 2004.

[15] R. M. P. R. Network, "Milparts news," 2004. http://www.milparts.net/2004 fall.html.

[16] E. Jones, "Apollo lunar surface journal," 2000. http://www.hq.nasa.gov /office/pao/History/alsj/.

[17] J. Rasmussen, A. Pejtersen, and L. Goodstein, *Cognitive Systems Engineering.* Wiley Series in Systems Engineering, New York: John Wiley and Sons, Inc., 1994.

[18] B. Shneiderman, *Designing the User-Interface: Strategies for Effective Human-Computer Interaction.* Reading, MA: Addison Wesley Longman, 3rd ed., 1998.

[19] S. Sullivan, *Virtual LM: A Pictorial Essay of the Engineering and Construction of the Apollo Lunar Module.* Space Series, Apogee Books, 2004.

[20] M. Jukes, *Aircraft Display Systems*, vol. 204 of *Progress in Astronautics and Aeronautics.* Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2004.

[21] "Luftpiraten.de," 2006. http://www.luftpiraten.de/glosh00.html.

[22] "Military analysis network," 2006. http://www.fas.org/man/.

[23] Headquarters, Department of the Army, *Technical Manual, Operator's Manual for UH-60A Helicopter, UH-60L Helicopter, EH-60A Helicopter*, tm 1-1520-237-10 ed., 2003.

[24] E. Sinclair, "AH-64A/D symbology display unit: Exportable training package," 3 Jan 2006.

[25] U.S. Marine Corps, *MV-22 Student Guide*, 2005. Marine Tilt-Rotor Training Squadron-204.

[26] J. Wolf and M. Barrett, "IFR steep-angle approach: Effects of system noise aircraft control augmentation variables," Report 700810, Honeywell, Inc., Minneapolis, April 1971.

[27] J. Franklin, *Dynamics, Control, and Flying Qualities of V/STOL Aircraft.* AIAA Education Series, Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2002.

[28] V. Merrick, G. Farris, and A. Vanags, "A head up display for application to v/stol aircraft approach and landing," NASA Technical Memorandum 102216, National Aeronautics and Space Administration, 1990.

[29] S. Chipman, J. Schraagen, and V. Shalin, "Introduction to cognitive task analysis," in *Cognitive Task Analysis* (J. Schraagen, S. Chipman, and V. Shalin, eds.), Mahwah, NJ: Lawrence Erlbaum Associates, Inc., 2000.

[30] M. Endsley, "Toward a theory of situation awareness in dynamic systems," *Human Factors*, vol. 37, no. 1, pp. 32 – 64, 1995.

[31] R. Haber and L. Haber, "Perception and attention during low-altitude high-speed flight," in *Principles and Practice of Aviation Psychology* (P. Tsang and M. Vidulich, eds.), Mawhaw, NJ: Lawrence Erlbaum Associates, Inc, 2003.

[32] F. A. Administration, *FAR/AIM 2005.* Aviation Supplies and Academics, Inc., 2004.

[33] L. Young, "Spatial orientation," in *Principles and Practice of Aviation Psychology* (P. Tsang and M. Vidulich, eds.), Mahwah, NJ: Lawrence Erlbaum Associates, Inc., 2003.

[34] G. Klein, *Sources of Power: How People Make Decisions.* Cambridge, MA: Massachusetts Institute of Technology, 1998.

[35] M. Avionics, "Stratomaster maxi single: Flight ii," 2006. http://www.mglavionics.co.za/Docs/flight2.pdf.

[36] "Flight instruments," 1995. http://www.allstar.fiu.edu/aero/PSI.htm.

[37] K. Bennett, "Graphical displays: Implications for divided attention, focues attention, and problem solving," *Human Factors*, vol. 34, no. 5, pp. 513–533, 1992.

[38] M. Buttigieg and P. Sanderson, "Emergent features in visual display design for two types of failure detection tasks," *Human Factors*, vol. 33, no. 6, pp. 631–651, 1991.

[39] P. Sanderson, J. Flach, M. Buttigieg, and E. Casey, "Object displays do not always support better integrated task performance," *Human Factors*, vol. 31, no. 2, pp. 183–198, 1989.

[40] J. Gibson, *The Ecological Approach to Visual Perception.* Boston: Houghton Mifflin, 1979.

[41] K. Vicente and J. Rasmussen, "Ecological interface design: Theoretical foundations," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 22, no. 4, pp. 589–606, 1992.

[42] J. Rasmussen, "Ecological interface design for complex systems: An example: Sead uav systems.," tech. rep., Wright-Patterson AFB: United States Air Force Research Laboratory, 1998.

[43] K. Bennett, M. Toms, and D. Woods, "Emergent features and graphical elements: Designing more effective configural displays," *Human Factors*, vol. 35, no. 1, pp. 71–97, 1993.

[44] B. Barnett and C. Wickens, "Display proximity in multicue information integration: The benefits of boxes," *Human Factors*, vol. 30, no. 1, pp. 15–24, 1988.

[45] J. Pomerantz and E. Pristach, "Emergent features, attention, and perceptual glue in visual form perception," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 15, no. 4, pp. 635–649, 1989.

[46] J. Rasmussen and K. Vicente, "Coping with human errors through system design: Implications for ecological interface design," *International Journal of Man-Machine Studies*, vol. 31, pp. 517–534, 1989.

[47] C. D. Wickens and J. G. Hollands, *Engineering Psychology and Human Performance.* Upper Saddle River, NJ: Prentice-Hall Inc, third ed., 2000.

[48] C. Wickens and A. Andre, "Proximity compatability and information display: Effects of color, space, and objectness of information integration," *Human Factors*, vol. 32, pp. 61–77, 1990.

[49] C. Wickens and C. Carswell, "The proximity compatability principle: Its psychological foundation and relevance to display design," *Human Factors*, vol. 37, no. 3, pp. 473–494, 1995.

[50] V. J. Gawron, *Human Performance Measures Handbook.* Mahwah, NJ: Lawrence Erlbaum Associates, 2000.

[51] M. Kutner, C. Nachtsheim, J. Neter, and W. Li, *Applied Linear Statistical Models.* McGraw-Hill Companies, 2005.

[52] NIST/SEMATECH, "Engineering statistics handbook," 2006. http://www.itl.nist.gov/div898/handbook/eda/section3/eda35a.htm.

[53] R. Lowry, "Subchapter 12a. the wilcoxon signed-rank test," 2006. http://faculty.vassar.edu/lowry/ch12a.html.