Design and Evaluation of an Achievability Contour Display for Piloted Lunar Landing

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Abstract

Landing on the moon requires the selection and identification of a location that is level and free of hazards, along with a stable, controlled descent to the lunar surface through the use of automated systems and manual control. Spatial disorientation may occur upon reentering a gravitational field after vestibular adaptation to microgravity during lunar transit. The workload associated with selecting a suitable landing point based on the remaining fuel and current vehicle states is a concern. In Apollo, visual out-the-window information was heavily relied upon to support the selection of a landing point, and there was little support information available to indicate whether the desired site was achievable.

A novel achievability contour display element showing the dynamic achievable landing area was developed based on a Goal-Directed Task Analysis and usability testing. A subject experiment was conducted in a lunar landing simulation environment to test the effects of the achievability contour on pilot performance, situation awareness, and workload in simulated approach and terminal descent scenarios as compared to an Apollo-style auditory display. Two control modes were used: supervisory control and roll, pitch, and yaw rate-control/attitude-hold (RCAH) manual control. The experiment also investigated differences in display effect with and without a required redesignation.

Results of the subject experiment (N = 10) indicate that the achievability contour display showed significant improvement in subjective situation awareness and workload ratings. The results also indicate a change in decision-making behavior with the use of the achievability contour display. There was no measurable difference in flight and landing performance measures between the two display conditions. The results of the experiment suggest that providing the achievability contour display may have beneficial effects on pilot situation awareness and workload during the final approach and terminal descent maneuvers. Additional research is needed to determine the optimal implementation and pilot interaction methods in the use of this display.

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List of Acronyms

AGC Apollo Guidance Computer

ALHAT Autonomous Landing and Hazard Avoidance Technology

CAU Cockpit Avionics Upgrade

CDR Commander

DEM Digital Elevation Map

DSF Draper Simulation Framework

DSKY Display and Keyboard

FTE Flight Technical Error

GDTA Goal-Directed Task Analysis

HUD Heads-up Display

LCD Liquid Crystal Display

LEO Low Earth Orbit

LIDAR Light Detection and Ranging

LM Lunar Module

LMP Lunar Module Pilot

LPD Landing Point Designation

MEDS Multifunction Electronic Display System

MSE Mean Square Error

NEO Near Earth Objects

PFD Primary Flight Display

POI Point of Interest

RCAH Rate-Command/Attitude-Hold

SA Situation Awareness

SAGAT Situation Awareness Global Assessment Technique

SART Situation Awareness Rating Technique

SEXTANT Surface Exploration Traverse Analysis and Navigation Tool

SS System Status

VFDE Vehicle Footprint Dispersion Ellipse

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1.0 Introduction

On July 20, 1969, the world learned that the first manned mission to the lunar surface was a success. The Apollo 11 landing represented the culmination of years of effort, and was a monumental accomplishment in engineering. The success of all the manned lunar landings hinged on the precise coordination of human pilots with complex systems. Not all parts of the landing occurred nominally, however. After a series of program alarms, Neil Armstrong and Buzz Aldrin neared the lunar surface. Armstrong was responsible for monitoring the location of the landing point through the use of etched markings on his window called the Landing Point Designator (LPD). Armstrong comments on the trip down to the lunar surface:

> "We could see the landing area and the point at which the LPD was pointing, which was indicating we were landing just short of a large rocky crater surrounded with the large boulder field with very large rocks covering a high percentage of the surface. I initially felt that that might be a good landing area if we could stop short of that crater… Continuing to monitor [the] LPD, it became obvious I could not stop short enough to find a safe landing area." –Neil Armstrong (Apollo 11 Technical Crew Debriefing, 1969)

This realization meant that Armstrong needed to either change the automatic landing target, or to use the hand controller to direct the lander to an alternate landing location. Armstrong describes the procedure:

> "I then proceeded to look for a satisfactory landing area and the one chosen was a relatively smooth area between some sizable craters and a ray-type boulder field. I first noticed that we were, in fact, disturbing the dust on the surface when we were something less than 100 feet; we were beginning to get a transparent sheet of moving dust that obscured visibility a little bit. As we got lower, the visibility continued to decrease." –Neil Armstrong (Apollo 11 Technical Crew Debriefing, 1969)

The task of redesignation was not limited to Apollo 11; in fact, every Apollo landing included at least one redesignation (Apollo 15 included 18 redesignations). In order to properly decide where to redesignate, the commander needed an unobstructed view of the landing area. This was not always easy; the lunar terrain provided challenges to the astronauts. Dust played an important role in several landings, as Armstrong suggests in the quotation above. In Apollo 12, the dust substantially increased the difficulty of identifying hazards on the lunar terrain below. As mission commander Pete Conrad indicated:

> "As soon as we got the vehicle stopped in horizontal velocity at 300 feet, we picked up a tremendous amount of dust; much more so than I expected. I could see the boulders through the dust, but the dust went as far as I could see in any direction and completely obliterated craters and anything else." –Pete Conrad (Apollo 12 Technical Crew Debriefing, 1969)

Another issue encountered during the Apollo landings that could hamper redesignation was geographic disorientation. The lack of easily recognizable landmarks and unusual reflectance properties of the lunar surface make it difficult to orient oneself relative to the target landing area. This was particularly an issue in Apollo 15, as described by commander Dave Scott:

> "When we pitched over, I couldn't convince myself that I saw Index Crater anywhere. I saw, as I remember, a couple of shadowed craters, but not nearly as many as we were accustomed to seeing [in simulation]." –Dave Scott (Apollo 15 Technical Crew Debriefing, 1971)

The accounts shown above underscore the necessity of the LPD task and the importance of having sufficient information for the commander to make an appropriate decision. Current and accurate information about hazards in the area of the landing site is critical to maintaining a safe landing. Accurate information about the current location of the vehicle and the location relative to any hazards is also important in maintaining the safety of the landing.

Displays are one method of providing this type of information to the pilot. Display technology has changed considerably since the days of Apollo. The Lunar Module (LM) supplied information to the commander and lunar module pilot through physical gauges and the Display and Keyboard (DSKY), which was an interface to interact with the onboard guidance computer. Since that time, the advent of glass cockpits, along with Heads-Up Displays (HUDs), synthetic vision displays, and modern computing power have transformed the cockpit. Investigations into some of these newer display techniques could help develop the interfaces of future lunar landing vehicles.

1.1 Motivation

The future of human spaceflight continues to emphasize the goal of sending manned exploration missions beyond low earth orbit (LEO). President Barack Obama has announced the intention to follow a "Flexible Path" plan to human space exploration, with a focus on manned missions to near earth objects (NEOs) such as asteroids, LaGrange points, and eventual manned missions to the Moon and Mars (Augustine, 2009). While the near-term focus remains on experiments aboard the ISS and other research platforms, the end goal is an improved understanding of the effects of long-term spaceflight on humans, which will directly support long duration missions to the lunar and Martian surface. Preparations and research for these longer-term missions must be performed far in advance to impact the design and development of vehicles and other technologies to support this effort.

As has been seen in the section above, the LPD task is a fundamental part of any planetary landing. If the vehicle is on a path into a potentially hazardous area, it is only sensible for the astronauts to have the capability to select a new landing site that is level and free of hazards, in addition to the option to abort. In the examination of the LPD task using Goal-Directed Task Analysis (GDTA), there are a series of decisions that the commander must make:

1. If the currently designated landing point is identified (through visual or display information) as hazardous, the commander makes the decision to change landing targets
2. Available alternatives must be identified
3. Based on a decision model (which may vary by pilot), the best alternate landing point must be selected

In order to successfully make these decisions to promote the greatest safety and success of the mission, the commander must have appropriate information available. The commander needs information about boulders, craters, steep slopes and other terrain hazards in order to decide if a redesignation is necessary (Paschall, 2009). In the 1960s, lunar surface mapping was not sufficient to identify small craters and boulders prior to the landing that were still large enough to pose a threat to the LM as it touched down. Instead, this was traditionally provided in Apollo through an out-the-window visual acquisition of the target landing area, combined with the pilot's estimation of the level of danger each hazard posed to the lander. To identify alternative landing areas, the pilot needed information about the terrain around the original landing target, such that sections without hazards could be noted. The pilot also needed information about the current and future states of the vehicle to determine if a particular alternative was achievable (that is, possible to reach safely). To select the best alternate, the terrain and vehicle state information would have to be combined with an internal decision model that might include relative danger from hazards, proximity to a location of scientific or other interest (such as Apollo 12), and fuel cost. In Apollo, the information sources were quite disparate: visual acquisition of the target and assessment of hazards had to be combined with fuel information given as a digital readout on a cockpit panel. Under the time pressure of a lunar landing, the decision of when and where to redesignate had to be based largely off of experience, training, and perhaps some piloting gut-feeling.

While all six of the attempted lunar landings in Apollo were successful, the lunar environment presented perceptual challenges to the astronaut that may have compromised some of the information being used to resolve these decisions, thus making them potentially compromised. Lunar dust blowback created by the descent engine obscured local hazards, as described earlier by Pete Conrad. Lunar regolith exhibits non-Lambertian reflectance properties (Dollfus, Bowell, & Titulaer, 1971), which can wash out details in the terrain if viewed either directly into or away from the sun. Both of these issues could compromise visual information being used in judgments during LPD. Also, the entrance of the astronauts into a reduced (relative to Earth) gravitational field combined with possible adaptation to microgravity during transit could create inconsistencies in the sensory information of the visual, vestibular, and somatosensory systems. If the pilot experiences spatial disorientation (SD), this could lead to erratic or incorrect control inputs similar to those seen in terrestrial cases of SD. In Apollo, with the lack of high resolution information about the lunar surface, the astronauts practiced in simulators that approximated what the astronauts would see out the window. However, these were not always accurate, and could lead to geographic disorientation, as was described above in Apollo 15.

With modern display technology and computing power, the decisions described above can be assisted by providing information that has already been combined to support LPD. Contemporary sensors and processing capability can provide detailed data on the terrain surrounding the landing target, including elevations, slopes, craters and boulders with much higher resolution than Apollo. With information about the achievable targets (based on fuel level and vehicle states) and the relative hazard levels of the local terrain, the pilot can make an informed decision during LPD while at a much lower workload than was seen in Apollo. Of course, it is logical that the commander would continue to use visual information and piloting experience to form an opinion and compare it to the system. However even in this case the displays could increase the confidence of the astronaut in their decision making process.

Earlier this year, President Obama unveiled a new plan of action for the National Aeronautics and Space Administration (NASA), supplanting the Constellation Program instituted by President Bush. Based on this plan, it appears that the human return to the lunar surface may be delayed as compared to Constellation. However, while the research and analysis presented here focus on lunar landing, it is very applicable to landings on other targets of interest identified by the President in the new plan, such as asteroids, Mars, and the Martian moons Phobos and Deimos. The task of Landing Point Redesignation is an important part of any flexible landing system, and the analysis presented herein could be used as a template and starting point for the development of displays for any extraterrestrial landing environment. Issues of dust, lighting, terrain hazards, and limited fuel will likely play a role in manned space exploration to any planetary body. Even with the delay of manned lunar landing, it is certain that once the preparations for the return to the moon are underway, the display design elements discussed in this report will be directly applicable.

1.2 Contribution

The research study presented herein aims to elucidate the benefits of including an achievability contour display as part of simulated lunar landings. This display approximates the achievable area of the lander based on current vehicle states and terrain information, and overlays it on a terrain map that will be provided by a sensor scan of the area around the landing point (see discussion of ALHAT in Chapter 2 for more information about the sensor scan and terrain map). These types of achievability contours have been proposed for spaceflight settings such as the space shuttle return to earth (McCandless, 2005), but have never been tested for the manned lunar landing setting.

An algorithm was developed to approximate the achievable landing area based on the vehicle states (primarily fuel), capabilities, and the local terrain information. Using this algorithm, an achievability contour display was designed based on prototype displays from the Autonomous Landing and Hazard Avoidance Technology (ALHAT) program. A primary flight display (PFD) was also modified for experimental use in lunar landing simulation. A series of scenarios were developed, focusing on the last phase of lunar landing, referred to as terminal descent.

In order to determine any beneficial effect of the achievability contour display, a baseline display was developed as a comparison. The baseline chosen for comparison was the information source used in Apollo for determining fuel criticality, an auditory call-out from ground control. Two control modes were developed for testing, a supervisory control mode and a manual control mode. The supervisory control mode represents the nominal case given the capabilities of the automatic lunar landing system, and the manual control mode operates in the rate-command attitude-hold (RCAH) that was used in Apollo during the terminal descent. A testing environment was developed using the Draper Simulation Framework (DSF) at Draper Laboratory. Models were created to simulate the vehicle dynamics, guidance, fuel use, redesignation capability, and terrain for simulated terminal descent scenarios.

Analysis includes a range of performance factors in landing, including flight technical error (FTE), fuel use, as well as range to the targeted aimpoint, attitude, and horizontal velocity at landing. Measures of workload include subjective and secondary task workload metrics. Situation awareness is assessed through subjective and performance techniques. These metrics are compared for differences between the use of the achievabilty contour display against an Apollo-style auditory display, across supervisory and manual control modes, as well as for redesignation and non-redesignation trials.

Future plans include the incorporation of the achievability contour concept as part of other advance display types (such as a HUD). Additional implementations of the contour will also be tested, including the impact of varying numbers of contours. Furthermore, the impact of multiple redesignation trials and the effect of highly variable vs. smooth terrain will be assessed in future experiments.

1.3 Problem Statement

This study aims to quantitatively and qualitatively investigate the benefits of the use of an achievability contour display during simulated lunar landing terminal descent scenarios under various control modes. The analysis will identify the usefulness or necessity of such a display for future lunar landings, and can inform interface design for next-generation vehicles. Since the achievability contour display presents information that is important in the LPD task (as determined by GDTA), it is expected that the contour display will show improvements over the Apollo-style auditory display. The following experimental hypotheses were developed for the testing:

Hypothesis 1: The achievability contour will result in improved situation awareness and workload as compared to an Apollo-style auditory display

Hypothesis 2: The achievability contour will be more effective in higher workload scenarios (manual control and/or required redesignations)

Hypothesis 3: The achievability contour will result in improved decision making during the landing point designation task

1.4 Thesis Outline

The remainder of the thesis is divided into 4 chapters, followed by references and appendices. Background information is presented to the reader in Chapter 2. It presents details on the challenges and elements of the LPD task, includes a discussion of previous implementations of achievability contours (such as the display element described), and discusses the use of ALHAT technologies as the basis for the development of the displays. Methods are detailed in Chapter 3, discussing the simulation environment and models created, assumptions used, display development process and redesigns, and the experimental testing methods and equipment. Chapter 4 is the Results section, which presents the display design products, as well as data and findings from the simulator experiment. The results are expanded upon in Chapter 5, the Discussion section. The discussion also outlines the limitations and implications of the results. This section also reviews the major findings and implications of the study, offers suggestions for supporting the LPD task, and identifies areas for further investigation.

2.0 Background

In the design of the achievability contour display, the tasks to be addressed must be investigated along with previous designs of similar spaceflight displays. This section begins by outlining the lunar landing task, with a focus on the task allocations and the landing point designation (LPD) task to which the achievability contour display acts as a decision aid. It concludes with a discussion of ALHAT, the currently proposed system to address the LPD task. The chapter continues with a discussion of historical displays in spaceflight, with particular highlights on previous displays that have shown achievability information. The chapter concludes with a discussion of display development and evaluation methods.

2.1 The Lunar Landing Task

Piloted Lunar landing represents a complex and demanding task on the system and human components of the mission. The vehicle must be capable of removing the high orbital velocity, be able to support both large and fine adjustments in position, able to avoid terrain hazards, and provide for the life support and safety of the crew. The crew must monitor the onboard systems, correct any navigational errors or uncertainties, ensure the safety of the targeted landing zone, recognize and execute an abort if necessary, and assume manual control of the vehicle when needed. For future landings, these responsibilities will be similar, though there may be advances in technology from their Apollo implementations. This section describes the phases and task assignments of past and future lunar landings.

2.11 Phases

Lunar landing begins with the lander vehicle in orbit around the moon. The phases of lunar landing are shown in Figure 1. After an initial transfer maneuver, the powered descent phase begins, which includes the maneuvers and descent down to the lunar surface. Within the powered descent phase, there are several sub-phases. The first subphase removes the remaining high orbital velocity by performing a long de-orbit burn, and is referred to as the “braking phase” (Figure 2). During the braking phase, the vehicle is far enough above the terrain to assume the most efficient attitude for deceleration. This results in the vehicle pitched back nearly 90 degrees, such that the astronauts are initially facing upwards toward the stars. The braking phase takes approximately 7-8 minutes, and ends when the guidance target conditions are satisfied, at an event referred to as “high gate”.

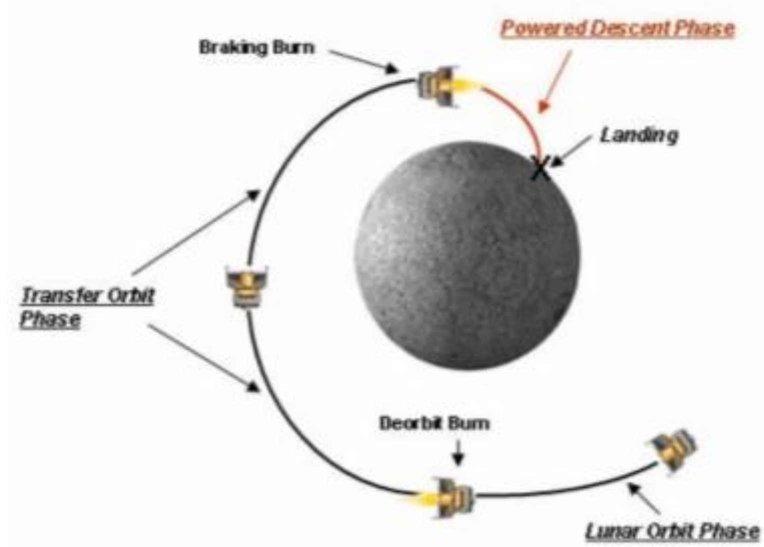


Figure 1. Phases of Lunar Landing (Sostaric R. , 2007)

After high gate the second subphase begins, called the "approach phase". The objective of the approach phase is to provide a stable platform for obtaining additional information about the landing area as the vehicle gets closer to the landing aimpoint. This involves an initial large forward pitch maneuver to bring the surface of the moon (and particularly the landing area) into the window view of the astronauts. For future landings, the vehicle attitude may also correspond to the optimal angle for sensor systems to scan the surface. During the approach, the task of landing point designation (LPD) begins, which is discussed in additional detail below. The approach phase includes a gradual forward pitch maneuver to bring the vehicle to nearly upright as it approaches the guidance target. In Apollo, the approach phase was designed to take approximately 105 seconds, and ends at "low gate".

At low gate the final phase of lunar landing begins, the "terminal descent phase" (called the "landing phase" in Apollo). The objectives of the terminal descent phase are to allow detailed assessment and final selection of the landing site, and allow maneuvering capability for the lander to perform a safe nearly vertical descent to the lunar surface. It was during this phase that the commander in the Apollo missions could assume a form of manual control over the vehicle, and this is discussed further below. The terminal descent phase lasts approximately 80 seconds, and finishes with safe vehicle touchdown on the surface. An additional schematic of the subphases of powered descent is shown in Figure 2.

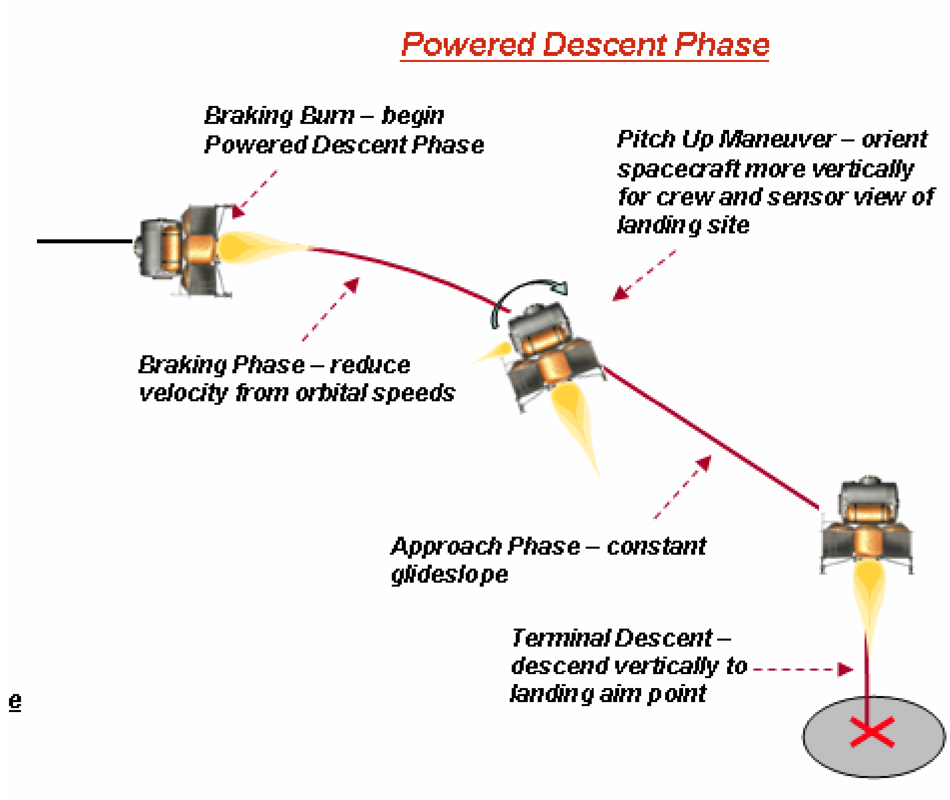


Figure 2. Subphases of Lunar Landing Powered Descent (Sostaric R. , 2007)

2.12 Challenges of the Lunar Environment

The lunar environment presents a unique set of stimuli to the human perceptual system that could degrade the safety of a manned landing. Unusual visual and vestibular sensory inputs could result in spatial or geographic disorientation, and potentially result in an incorrect response from the astronauts. For an in-depth discussion of potential perceptual difficulties and incidence of disorientation during lunar landing, see Appendix I.

2.13 Task Allocation

The lunar landing task involves cooperation between human and automated elements of the landing system. In Apollo, the humans monitored the automated systems, input commands to the Apollo guidance computer (AGC), identified navigational landmarks, selected a landing target, and provided control inputs to the flight path and attitude of the vehicle in the final stages of flight. The human tasks varied thought the phases of landing. During the braking phase, the astronauts were responsible for PDI, and monitoring the vehicle states to ensure that the automatic guidance was commanding the proper maneuvers that would set the vehicle on the nominal trajectory towards the lunar surface. Monitoring flight systems typically involved querying the AGC via the display and keyboard (DSKY), which contained three registers of information for the astronauts (Mindell, 2008). During the approach phase, the astronauts could make visual contact with the surface and began looking for navigational marks (e.g. distinct formations of craters) in addition to continued monitoring of the automated systems. When visual contact was made of the landing area, the commander was also responsible for performing the LPD task with the support of information from the AGC. During terminal descent, the astronauts made the final selection of landing aimpoint, and could take control of the vehicle for the final portions of the trajectory. This control was enacted through several inceptors in front of the commander's seat. Through these inceptors, the commander had rate-control/attitude-hold (RCAH) command of the vehicle and incremental control of rate-of-descent. In RCAH, a deflection in the inceptor corresponds to a command in rate of change of attitude, and letting the inceptor return to the neutral position corresponded with maintaining a particular attitude (no change commanded). Attitude rate control was achieved through firing sets of smaller reaction control system (RCS) thruster pairs. Incremental rate of descent was controlled through the deflection of a separate inceptor, with each deflection corresponding to a change in descent rate of 1ft/sec.

Future lunar landings are planned to have similar task allocations as those in Apollo (Paschall, 2009). Glass cockpit displays will be available to provide flight information and support the out-the-window view of the terrain. Sensor systems including flash light detection and ranging (LIDAR) will scan the landing area and identify local hazards that could compromise the safety of the lander (Epp C. R., 2008). This information will be provided to the astronauts along with suggested landing aimpoints as calculated from automated algorithms. The Apollo LM used the RCAH mode, but future vehicles are likely to be considerably larger and therefore more difficult to control if thruster sizing and control modes are not modified from Apollo (Billimoria, 2008). Considerable research needs to be performed regarding the implementation of displays and control modes for future lunar landings.

2.2 Landing Point Designation

Landing point designation is defined as the acquisition of information, identification, and selection of an appropriate landing aimpoint. The landing point designation task promotes the safety of the mission and crew by allowing the astronauts to obtain detailed information about the landing area and possible landing aimpoints, and to evaluate the safety of these aimpoints to provide for an appropriate selection of an aimpoint. LPD arises from the acknowledgement that lunar surface data from orbit is insufficient to fully characterize the safety of a particular landing aimpoint to adequate certainty. Therefore, as the lunar landing vehicle descends to the surface, it becomes required for human or sensor systems to obtain more detailed information about the local surface in the landing area of interest. This includes information about local hazards such as craters or boulders, as well as information about the slope and roughness of the surface (Cohanim, 2009). Once this information is obtained, the set of safe and appropriate (e.g. based on mission parameters) landing aimpoints on the same size scale as the lander footprint can be identified, and an aimpoint can be selected by either the astronaut or by automated algorithms. It is this task that the proposed achievability contour provides assistance through information about the achievability of each landing aimpoint, thus ensuring that an achievable landing location is selected.

2.21 Apollo LPD

In Apollo, the human played an important role in the LPD task. The standard trajectory (shown in Figure 2) includes a large pitch-forward maneuver during the approach phase to bring the landing area into the astronaut's view out the window. This view was used to judge the safety of the aimpoint where the current trajectory would bring the lander, along with the safety of alternate aimpoints in case the initial target was deemed unacceptable. Etchings on the lunar module window were used to pinpoint the location on the surface that represented the current landing aimpoint based on numeric angle readouts from the AGC shown on the DSKY. Images of the lunar module window etchings and the DSKY are shown in Figures 3 and 4, respectively. Any designation to an alternate target was performed by deflecting an inceptor, which incremented the location of the landing target on the surface. All of the Apollo landings included at least one change in designated landing aimpoint, and some included many (See all Apollo Mission Reports).

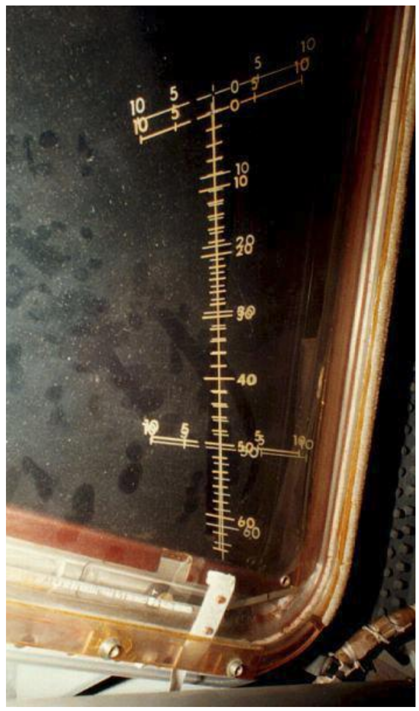


Figure 3. Etchings on lunar module window for use in LPD

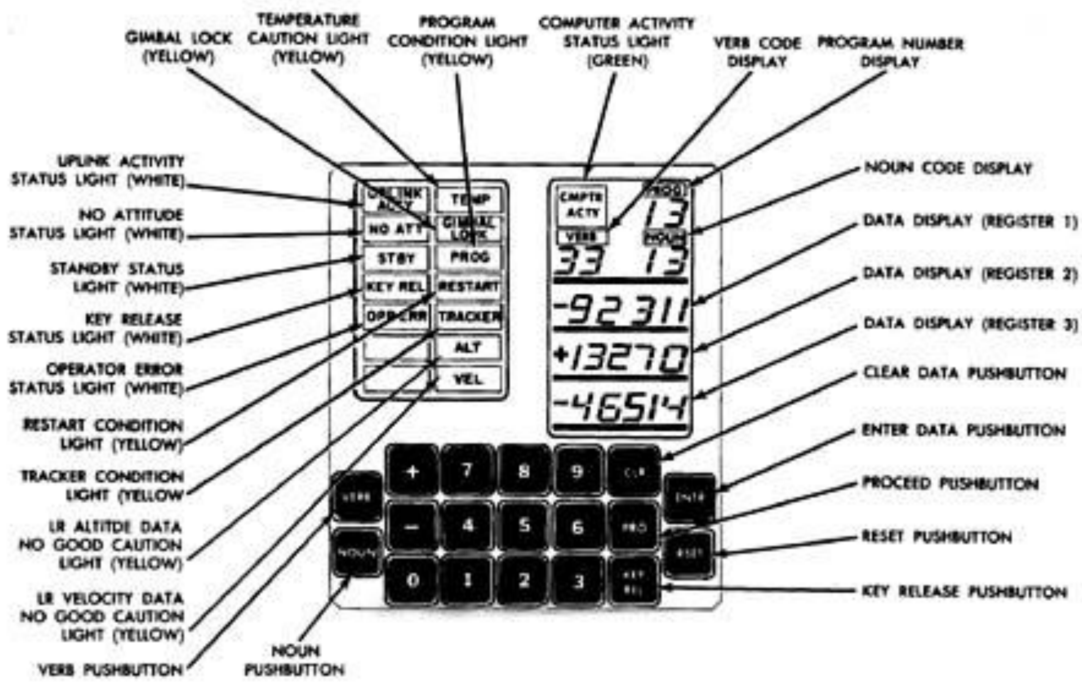


Figure 4. Apollo Lunar Module Display and Keyboard (DSKY)

During the Apollo 11 mission, one of the changes in designated landing aimpoint came late in the trajectory, and required a considerable use of propellant to pilot the vehicle beyond a dangerous boulder field (Apollo 11 Technical Crew Debriefing, 1969). As part of the decision to modify the landing aimpoint, the commander had to determine whether the alternate landing aimpoint was achievable based on the current vehicle states (including descent engine propellant), along with knowledge of the vehicle capabilities. While a particular alternate may be desirable based on terrain information, a high fuel cost associated with the maneuver to achieve the new target may reduce the overall safety of the alternate. Apollo provided fuel information in several different ways: fuel and oxidizer level (in %) were available on the center instrument panel between the commander (CDR) and lunar module pilot (LMP), and the astronauts were also provided an auditory warning as they approached a go/no-go decision point known as BINGO (LM 11 Operations Handbook Volume II: Operational Procedures, 1971). BINGO represented the time at which 20 seconds of propellant burn in hover were remaining, and ground control provided 60 and 30 second warnings prior to this event. These pieces of information gave the astronauts information about the current fuel level and therefore the criticality of fuel in the consideration of alternate landing aimpoints.

2.22 Future LPD

For future lunar landings, it is planned that the astronauts will have accurate sensor systems that will scan the lunar surface and provide the terrain information to the pilot through the use of displays (Paschall, 2009) (Major, Cohanim, & Brady, 2008). An automated system will determine suggested landing aimpoints, and present these to the astronauts. The astronaut can then designate a landing aimpoint based on both the information from the sensor scan along with information from out-the-window views of the lunar surface. In a situation such as that encountered in Apollo 11, it would be useful for the astronauts to have information about the achievability of any particular landing aimpoint, such that the remaining fuel at landing could be estimated prior to changing landing targets.

2.3 Autonomous Landing and Hazard Avoidance Technology (ALHAT)

ALHAT is a NASA project to develop a system to promote the safety of future lunar landings by including a sensor scan of the surface that is used to identify hazards and safe landing sites (Epp C. R., 2008). This includes analyzing the trajectory tradespace and vehicle motions to promote the ability to scan the surface and provide an out-the-window visual for the astronaut (in the case of manned landings) (Epp & Smith, 2007) (Paschall, 2009). The current design includes a system that scans the target landing area just after the forward pitch maneuver during the approach phase (approximately 1-2km altitude). This scan creates a digital elevation map (DEM) of the lunar surface with the ability to detect a vertical height changes and slopes in the terrain (Forest, Cohanim, & Brady, 2008). The DEM is then run through an onboard algorithm that computes values for the slope and roughness of the terrain at each point on the map, and uses this information to identify hazards that could compromise the safety of the lander (e.g. craters, boulders, steep slopes). The system then computes a rating for each point on the map based on a weighted combination of slope, roughness, delta-V cost, distance to hazards, and possibly distance from point of interest (POI) ratings (Needham, 2008). Based on these ratings, a set of “suggested” landing aimpoints is determined by selecting the highest rated points (typically with a requirement to be separated by some minimum distance). For unmanned landings, the system automatically selects the top rated aimpoint, and the guidance adjusts the vehicle trajectory to land at that location. For manned lunar landings, these suggested aimpoints are presented to the astronauts on an interactive display that will allow them to select a location on the map (not required to be one of the top rated points), and to verify this selection. The location of the selection is then input to the guidance computer which will direct the vehicle to the selected aimpoint. This system plays an important role in supporting the LPD task by providing detailed information about local hazards to the astronauts during the approach phase. The exact form of this interactive display has not been fully determined, though some of the preliminary designs will be discussed in more detail in the display section below.

2.4 Displays in Spaceflight

Displays have played a critical role in aviation since the 1930s, and were included in the development of the vehicles for the American space program. Displays can improve the situation awareness of the pilot and reduce mental workload by providing information about the vehicle and the environment. Past and future manned spacecraft all include the consideration of displays in the design process.

2.41 Apollo Displays

By the time of the Apollo program, gauges showing altitude, airspeed, attitude, fuel, and other vehicle states were common in aircraft. Apollo engineers were aware that providing accurate information on the vehicle states to the astronauts was important for improving the safety of the mission, particularly during manual control. The lunar module (LM) included several instrument panels that contained gauges providing this information to the astronauts (see Figure 5). Tape displays, digital readouts, an attitude eight-ball, and a variety of switches comprised the center panel 1, which acted as the primary commander instrument panel (Lunar Module Systems Handbook: LM-5 to LM-9, 17 January 1969) (see

Figure 6). These mechanical types of displays were supplemented by a new type of interface, the DSKY. The DSKY provided a method for the astronauts to interact with the AGC through a specially developed language that included “verbs” and “nouns”. The DSKY had three registers to display numeric information from the guidance computer (e.g. altitude in ft). Using this interface, the astronauts could input commands to the AGC, request certain readouts, or give approval to proceed.

Figure 5. Lunar Module cabin control display panels (Mindell D. , 2008)

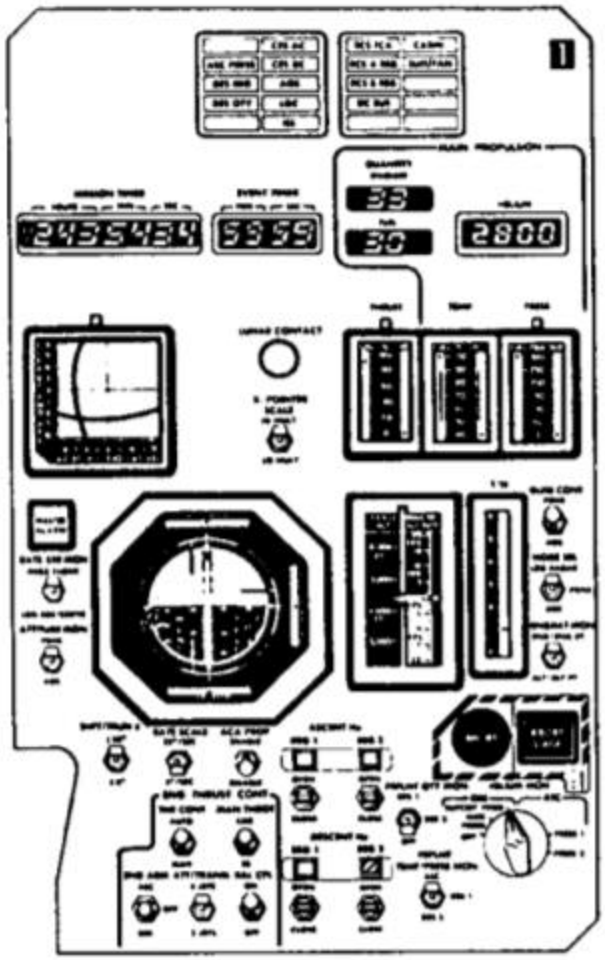


Figure 6. Apollo Lunar Module Center Panel 1 Instrumentation (Apollo Operations Handbook, Lunar Module, LM 10 and Subsequent, Volume I, Subsystems Data, 1971)

In Apollo, these displays were supported by a communications channel with ground control in Houston (CAPCOM) and by paper checklists and information sheets. The achievability display information developed in this report was not available to the Apollo astronauts on a dynamic scale. However, engineering diagrams had been created to identify the achievable landing area, also called the “landing footprint”, for a series of altitude points throughout the trajectory (Cheatham & Bennett, 1966). An example of these diagrams is shown in Figure 7. These paper diagrams were available to the astronauts during landing, although the static nature, lack of terrain elevation information, and mental workload of computation would have limited their usefulness during LPD.

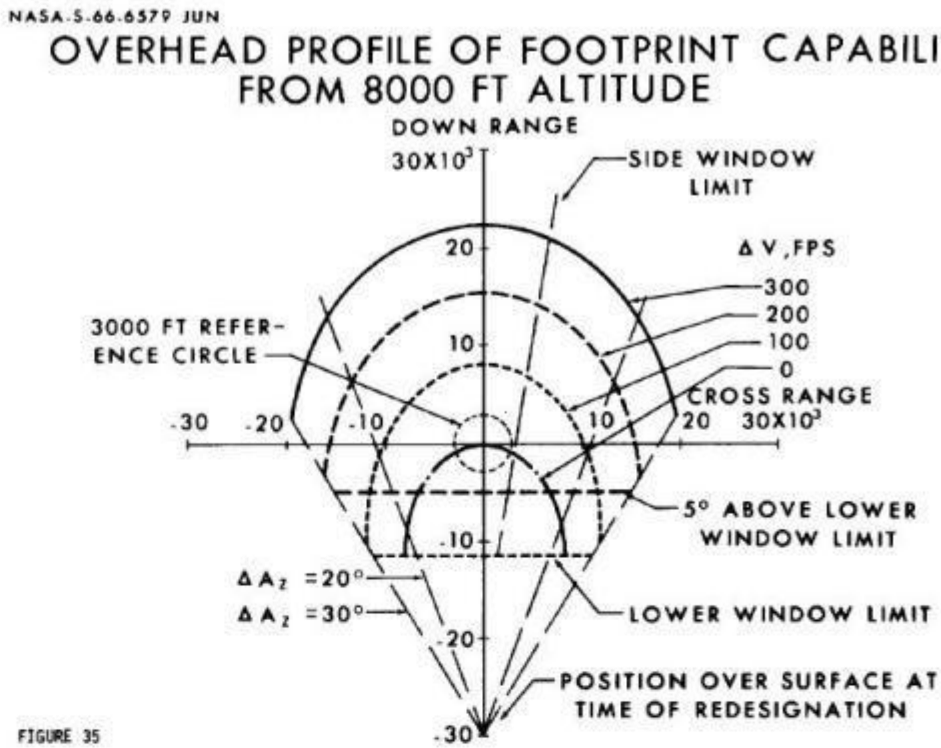


Figure 7. Apollo landing footprint (Cheatham & Bennett, 1966)

2.42 Shuttle Displays

The displays for the Space Shuttle, designed in the 1970s, used the most advanced technology available at the time. This primarily included electromechanical gauges and cathode ray tube (CRT) screens for the cockpit (McCandless, 2005). Even as these technologies became dated, there were no major upgrades to the shuttle display system until 2000. At this time the Multifunction Electronic Display System (MEDS) entered flight, replacing the older displays with liquid crystal display (LCD) equivalents and reducing the maintenance needed. Figure 8 shows the MEDS cockpit. However, even with the new display technology, the underlying human factors issues were not addressed (e.g. colors, related information proximity, missing information). This realization lead to the proposal of the cockpit avionics upgrade (CAU). This would supply a new set of integrated displays designed to correct these issues. These displays were developed but never implemented in the shuttle. Of particular note in these displays is the horizontal situation entry display, which shows similar information to the achievability contour display for lunar landing that is the topic of this report. The CAU version of the horizontal situation entry display is shown in Figure 9. It includes static achievability contours in the upper left corner of the display, representing the landing footprint of the shuttle. The “house” object (containing KSC and NKT in this image) represents landing within nominal range of energy (based on the unpowered gliding of the vehicle. The expanded area (containing YHZ) represents the capability to achieve the target, but only if special flying techniques are employed. Landing points within this area are colored yellow to indicate some risk involved in their selection. If a particular landing site is unachievable, it is colored red and lies outside of the landing footprint (not shown in this image). In this display, the contours are static, and the landing points move to indicate their current state. This display is also used in the Shuttle Abort Flight Manager (SAFM) to provide information during ascent aborts.

Figure 8. Multifunction Electronic Display System (MEDS) cockpit (McCandless, 2005)

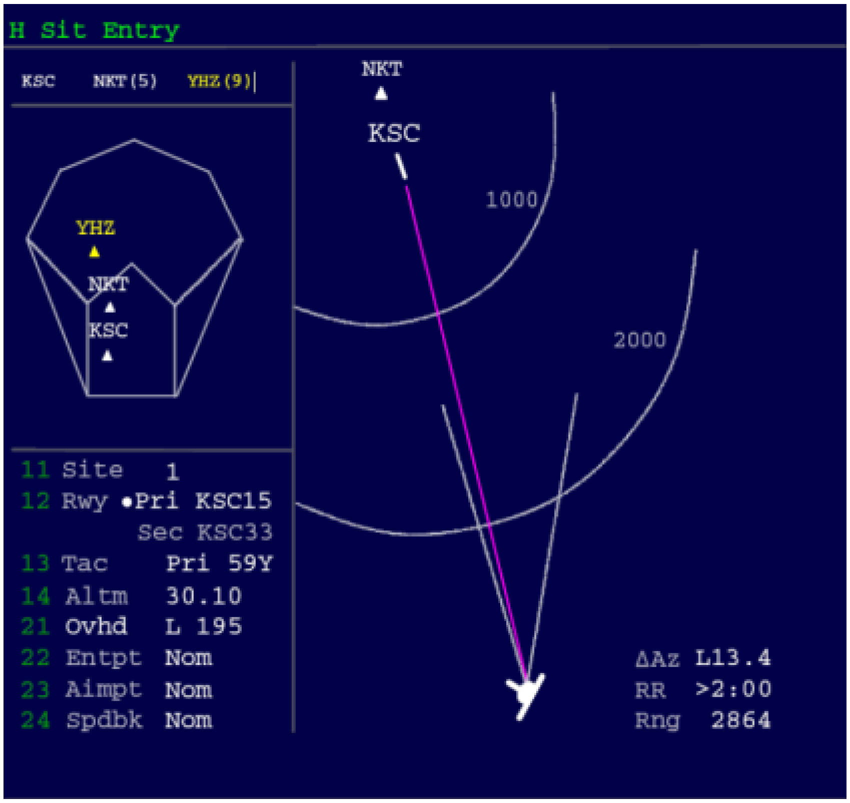


Figure 9. Cockpit Avionics Upgrade (CAU) Horizontal Situation Entry Display (McCandless, 2005)

2.43 Future Lunar Landing Displays

The display and interface design process for future lunar landings is still in its infancy, since the vehicle parameters have not been fully solidified yet. However, some previous research has been done to propose displays that might be considered for future landings. One set of displays developed includes a Landing Zone (LZ) Display, a Situational Awareness (SA) Display, and a System Status (SS) Display (Cummings & Wang, 2005). In this layout, the LZ display contains primary flight information, hazard information, and a redesignation mode for LPD. An image of the redesignation mode is shown in Figure 10. In this mode, the overall achievability limits are not shown to the user, though the estimated fuel remaining at touchdown is shown as an additional fuel gauge (with blue bar) just to the left of the main fuel gauge. This provides some similar support to the achievability contours, given that an alternate landing point that would result in no fuel remaining (outside the vehicle achievability limit) would be reflected in the secondary fuel gauge. However, it would require the user to select several points on the map to get an idea of where this limit exists in the top-down view, and is not conducive to showing multiple alternatives at once (since each would require its own secondary fuel display). Some additional baseline displays have been developed to display hazard, landing aimpoint, and elevation information to the pilot during LPD (Needham, 2008) (Chua, Major, & Feigh, 2009). An example of these displays is shown in Figure 11. In this display, a top down view of the landing area is presented, with the locations of the selected landing aimpoints. It includes visualization of the Vehicle Footprint Dispersion Error (VFDE), which shows the diameter of the vehicle footprint plus an error term. The green oval is a fuel contour showing the maximal achievable area, similar to the proposed achievability contours. However, this contour used an elliptical approximation and was not implemented dynamically or inclusive of elevation information. Recent displays like those in Figures 10 and 11 were used as a baseline for the creation of the achievability contour display discussed further below.

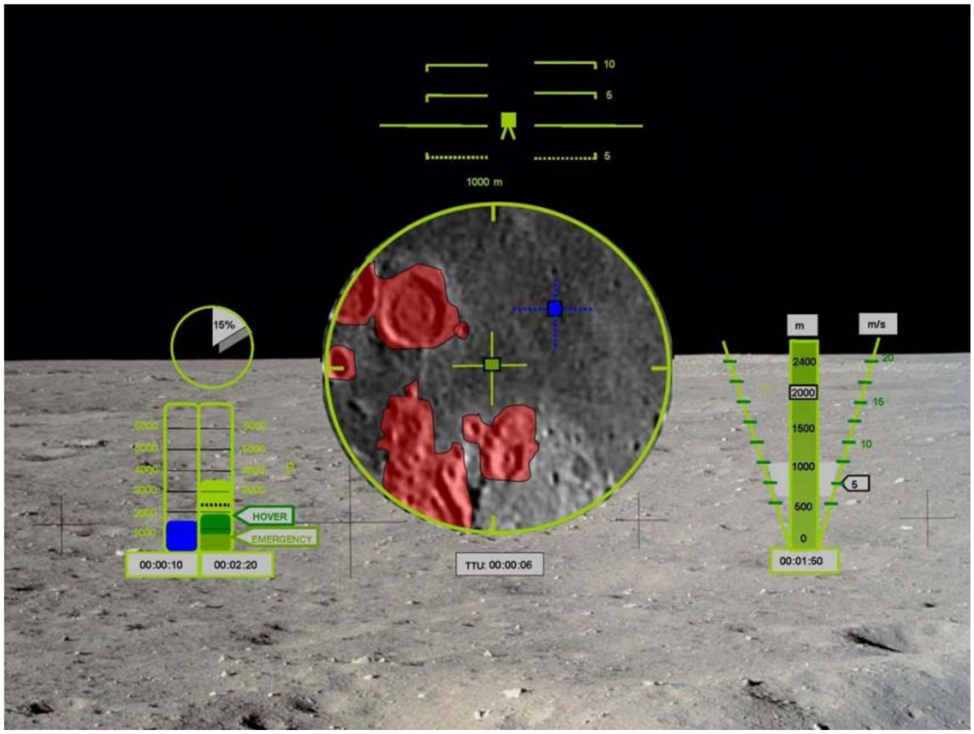


Figure 10. Redesignation mode display from (Cummings & Wang, 2005).

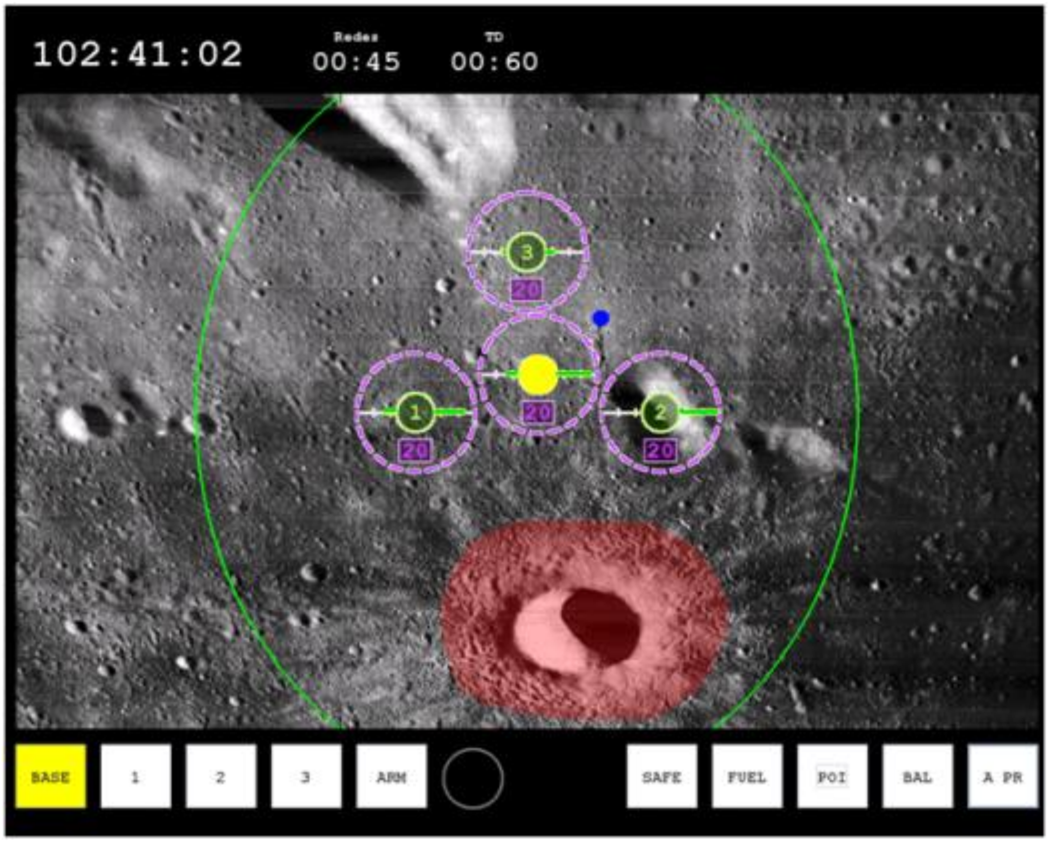


Figure 11. Landing Point Redesignation display from (Chua, Major, & Feigh, 2009).

2.5 Display Development/Evaluation

There are many techniques for assisting the development and evaluation of a novel display, several of which are highlighted here. The first section below discusses goal directed task analysis as a tool to define the information requirements for display development. Then usability testing as a display evaluation method is discussed. This section concludes with a definition of situation awareness and its measurement as an important metric for display evaluation.

2.51 Goal Directed Task Analysis

Typically, a display is created to meet the information needs for a particular task. There are many forms of information needs analysis, including user surveys and task analyses. In the development of the achievability contour display, a goal directed task analysis (GDTA) was performed. Goal Directed Task Analysis is a form of cognitive task analysis to identify the important pieces of information needed to perform a particular task or series of tasks (Endsley, Bolte, & Jones, Designing for Situation Awareness: An approach to user-centered design, 2003). The process involves breaking the overall task into subtasks, and identifies the decisions required to perform each subtask. The information needed to quickly and correctly make these decisions can be tabulated and become the information requirements for display design.

2.52 Usability Testing

Usability testing refers to a range of tests to evaluate the general usefulness of a display. Common implementations include heuristic evaluation, cognitive walkthrough, pluralistic walkthrough, and user testing. For the achievability contour display, usability testing was executed in the form of pluralistic walkthrough (Helander, Landaurer, & Prabhu, 1997). This method of evaluation involves showing the display to subject matter experts, and walking through the elements and the tasks to which the display is intended to apply. The experts provide comments during the walkthrough about elements of the display and their usefulness.

The other form of usability testing applied in the evaluation of the achievability contour is user testing. This method involves the creation of a working version of the display, and selecting users to test the display in a realistic setting. In this case, a lunar landing simulation was created and a subject experiment was conducted to provide user testing as an evaluation of the achievability contour display.

2.53 Situation Awareness

Improving situation awareness (SA) is a common and important goal in display design. The traditionally accepted definition of situation awareness comes from (Endsley, 1995):

> "The perception of environmental elements within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future."

Following this definition, there are three elements of situation awareness: Perception, Comprehension, and Projection (Figure 12). The achievability contour display addresses both comprehension, through the direct display of the current achievable area, and projection, by providing a prediction of a successful landed state for all areas within the contour.

There are many techniques for measuring situation awareness. Among the simplest are subjective rating scales, such as the Situation Awareness Rating Technique (SART) used in the experiment to evaluate the achievability contours (Taylor, 1990). After each trial, the subject provides a rating from 1 (low) to 7 (high) on three scales: Demand on attentional resources, Supply of attentional resources, and Understanding of the situation. The first rating (demand) corresponds to the amount and complexity of information presented in the scenario. The second rating (supply) assesses the capacity and concentration of the subject's attentional resources to the task. The third rating (understanding) rates the quantity and quality of information that the subject receives from the interface.

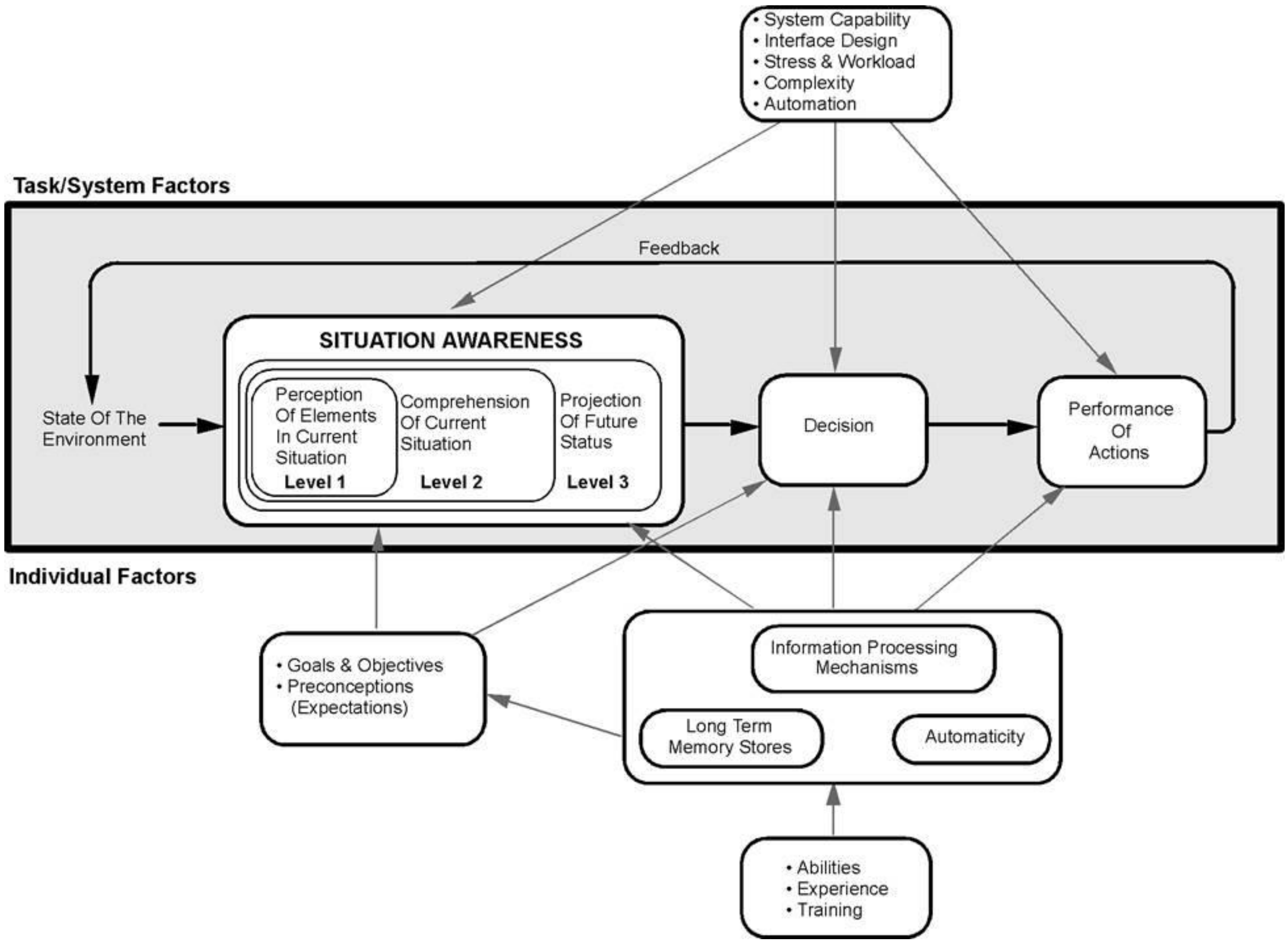


Figure 12. Model of situation awareness, adapted from (Endsley, 1995)

Alternate methods of measuring situation awareness include freeze techniques such as the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1995), and verbal protocols. These techniques involve pausing the simulation in the middle of the scenario and ask direct questions about information that is important to good situation awareness. SAGAT has been shown to be a valid measure of SA, but is intrusive on the scenario. Since it would have limited the ability to measure performance parameters all the way to touchdown, freeze techniques were not used in the evaluation of the achievability contours. Verbal protocols instruct the subjects to "speak aloud" their thoughts and knowledge of the situation. By recording these protocols, one can deduce the level of situation awareness that the subject had throughout the trial. A modified version of verbal protocols was implemented in a recent thesis that required the subjects to perform verbal callouts of important states, which was able to track SA through time (Hainley, 2010). A discussion of the use of these types of verbal protocols for future experiments is included in Chapter 5.

3.0 Methods

3.1 Display Design

The achievability contours were identified as an important element in the LPD task through a cognitive task analysis. The contours were designed using general human factors guidelines with the goals of providing the necessary achievability information to the astronauts while minimizing mental computations needed to process the information. Initial display concepts were created based on previous LPD display designs (Chua, Major, & Feigh, 2009), and terrain maps were created through the modification of previously generated DEMs (Cohanim, 2009). Additional revisions of the experimental displays were created utilizing usability testing with Apollo astronauts as experts.

3.11 Goal Directed Task Analysis (GDTA)

A GDTA was created for the LPD task, and a summary is shown in Figure 13 below. Achievability information was identified as important for several of the decisions involved in the LPD task. The term "achievability information" specifically refers to the following pieces of information:

- The area that the vehicle can safely reach at the current point in time based on vehicle states and capabilities
- The real-time availability of each of the landing aimpoints as suggested by the automatic system
- An estimate of the time until each of the suggested landing aimpoints becomes unavailable

3.12 Design Guidelines and Goals

Design guidelines were drawn from several sources (Brown, 1999) (Tsang & Vidulich, 2003)for the design of the achievability contour display element. Referring to these sources, primary importance was placed on the principle of information need, the principle of compatibility, and the principle of pictorial realism. Based on the achievability information requirements generated in the GDTA, a contour was determined to fit these needs. The contour represents the current achievable limit of the vehicle, and thereby includes information about the achievable area and availability of any particular point on the DEM. With real-time updates of this achievability limit, the rate of closure of the contour and therefore the time until a point on the surface is unavailable can be estimated.

The primary goals of the display design were to maintain simplicity, provide pertinent information, and minimize mental workload in processing the information presented. Simplicity was maintained in the contour design by minimizing the physical space and alphanumeric characters used in the display element. The achievable limit was deemed sufficient to indicate the achievable area of the lander (rather than displaying the area itself), and alphanumerics were considered unnecessary to convey the required information. To minimize computational effort for the user, the achievable area of the vehicle is approximated automatically by the system computer. The intuitive nature of the achievability contours also require very little computation to quickly obtain information about the general criticality of the fuel state and identify which landing aimpoints are still achievable.

Alternate achievability display methods were considered, including using timers or color changes to indicate the dynamic achievability of each landing aimpoint. However, these ideas were discarded in favor of a contour display since they only provide information about the suggested landing aimpoints, and thus do not provide information about the entire achievable area. The complete achievability information would prove important if the astronaut decided to designate a target based on out-the-window visual inspection that did not specifically match a landing aimpoint suggested by the system. The principle of pictorial realism suggests that a display element should match the physical interpretation of the information being presented. In this case, the achievable area physically represents an amorphous shape overlaid on the lunar terrain. The representation of the outer edge of this shape as an achievability limit matches the physical form of the information.

Two displays were developed for the experiment. A primary flight display was modified from previous research, and several display elements were added. A list of major changes to the primary flight display is listed below in Figure 14. An image of the experimentally implemented primary flight display is shown in Figure 15 below. The second display is referred to hereafter as the horizontal situation display. This display was developed based on previous designs from ALHAT research (Chua, Major, & Feigh, 2009) (Forest, Cohanim, & Brady, 2008), and includes a DEM with hazard and landing aimpoint location overlaid on the map. This information is portrayed in a top-down egocentric format. The landing area display contained additional elements that included a spacecraft symbol, numeric range readout for the primary landing aimpoint, time-to-touchdown digital clock, alerting light, and the achievability contours (in trials that included the contour condition).

Subgoal	Task	Decision	Information Requirements
Supervise Safety of Landing Aimpoint	Detect Anomalies in Landing Aimpoint	Are there unexpected hazards in the currently designated landing aimpoint?	• Terrain parameters (slope, roughness, presence of boulders/craters) • Visual observation
	Assess Hazard Level of Anomalies (if detected)	Does the landing aimpoint need to be changed?	• Terrain parameters • Visual observation
	Redesignate Landing Aimpoint (if necessary)	What other possible landing aimpoints are currently available?	• Suggested landing aimpoints • Visual observation • Vehicle states • Vehicle capabilities • Achievability information
		What is the level of safety for each of the potential landing aimpoints?	• Automatic system rating score • Perceived hazard rating (from visual observation)
		Which landing aimpoint is the best?	• Automatic system rating score • Perceived hazard rating (from visual observation)
Supervise Vehicle Navigation	Monitor Vehicle States	Are there any anomalies in the vehicle states?	• Vehicle states • Vehicle capabilities
	Manually Maneuver Spacecraft (if necessary)	Are there any anomalies in the vehicle states?	• Vehicle states • Vehicle capabilities
		Is the lander on the correct navigation track?	• Vehicle states • Navigation information
		Is the target location achievable?	• Vehicle states • Vehicle capabilities • Visual observation • Achievability information
Abort Mission (if Necessary)	Abort	Is the mission safely achievable?	• Detected anomalies/failures • Abort to ground criteria • Abort to orbit criteria • Vehicle states • Vehicle capabilities

Figure 13. Summary of Information Requirements generated by Goal-Directed Task Analysis

Element	Location	Modification
Horizontal Situation Indicator	Bottom Center	Added “doghouse” style landing target display
Horizontal Situation Indicator	Bottom Center	Added box with numeric readout of range and horizontal velocity
Mode Annunciator	Upper Right	Element added to indicate current control mode (“A65” = supervisory, “A66” = manual) and vertical status (“AUTO” = normal descent, “HOVER” = commanded hover)
Attitude Numeric Readout	Upper Right	Element added to indicate Roll/Pitch/Yaw attitude
Velocity Numeric Readout	Lower Right	Element added to indicate XDOT/YDOT/VDOT velocities (forward, side, and total horizontal velocity, respectively)
Descent Rate Numeric Readout	Right	Element added below tape gauge to indicate descent rate numerically
Guidance Needles	Center	Element added to provide “fly to” guidance cues, scaled to match pitch ladder

Figure 14 Modifications to primary flight display for experiment

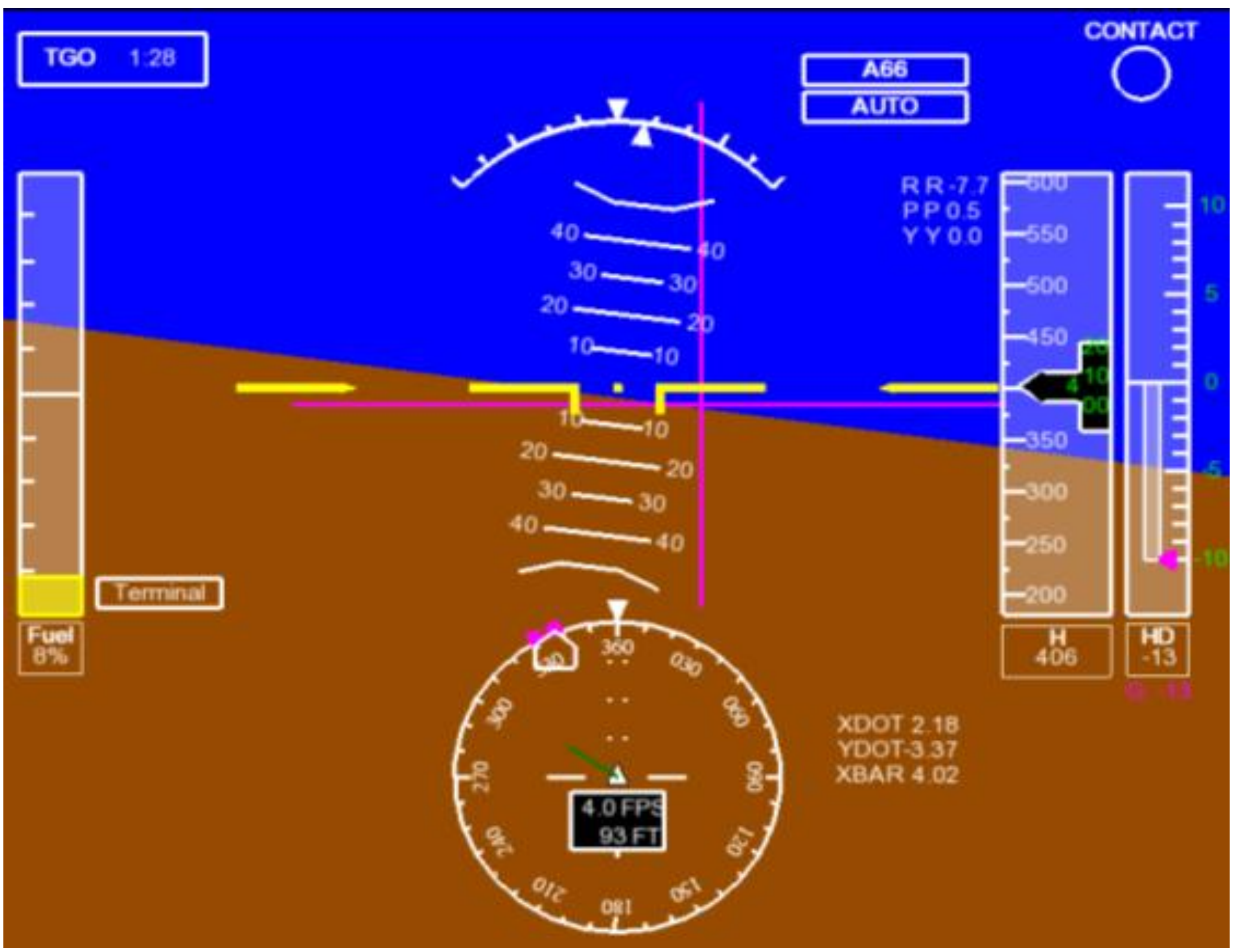


Figure 15. Experimentally implemented primary flight display

3.13 Usability Testing

Usability testing in the form of pluralistic walkthrough was conducted to evaluate the both the primary flight display and the achievability contour display. Three Apollo astronauts (2 LMP, 1 CDR) were invited to act as the subject matter experts for the achievability contour display evaluation. Each walkthrough was done individually on a different date. Comments and suggestions about the display were noted and used to iterate on the display design. The comments were parsed into one of three categories:

1. Change should be implemented prior to experimental testing
2. Change should be implemented in future studies of the achievability display
3. Change needs further investigation before implementation

Those changes falling into the first category were incorporated into the experimental display setup described below and in Chapter 4. Notes on the other two categories are documented in Appendix II, and should be investigated in further studies.

3.14 Map Development

Four DEMs that were deemed representative of possible future lunar landing areas were selected for use in the experiment, with one designated training map and three experimental maps. Comparable DEMs were analyzed with the ALHAT hazard identification algorithm (Cohanim, 2009) to create a hazard map that could be overlaid on the DEM. The base hazard map was modified using the Surface Exploration Traverse Analysis and Navigation Tool (SEXTANT) software developed at the Massachusetts Institute of Technology (Johnson, 2010). Two additional modified incarnations of the base hazard map were created for each of the three experimental maps, for a total of nine map conditions for experimental use in addition to the training map. Images of the experimental maps used are included in Appendix III.

3.2 Simulator Development

A simulation of the approach and terminal descent phases of flight was developed in the Draper Laboratory fixed-base simulator. Displays were created using GLStudio v3.2 (DiSTI, www.simulation.com) and OpenGL code, and models of the vehicle and achievability contour calculation were coded in MATLAB Simulink. A single gaming joystick (Saitek, Cyborg EVO gaming joystick) was used as the inceptor. Deflection of the joystick in each of the three axes controlled roll, pitch, and yaw rate commands for the vehicle when in manual control mode. The joystick trigger was used to cycle through the landing aimpoints. Two of the buttons on the top of the joystick were utilized for the subjects to respond to the side task alert signals, as described in more detail below.

3.21 Vehicle and Trajectory Parameters

The vehicle dynamics and control model was derived from the Altair LDAC-1 Delta vehicle parameters (Duda, Johnson, & Fill, 2009), and guidance laws were implemented to follow a reference trajectory (Billimoria, 2008). In the RCAH control mode, the pilot commands an attitude rate which tilts the thrust vector and accelerates the vehicle in the direction of the tilt (a third order control system). The flight control system was modeled such that the commanded attitude rate was linearly proportional to the inceptor displacement with a maximum of 30 deg/sec in pitch and roll and 20 deg/sec in yaw at full inceptor deflection. When the pilot zeroed any inceptor deflection, the attitude rate was nulled and the tilt angle of the vehicle was automatically held constant. The control system was modeled to have a small (2 millisecond) time delay, and the sizing and placement of the LDAC-1 Delta vehicle reaction control system thrusters resulted in a maximum achievable attitude acceleration (control power) of 3.0 deg/sec^2 in pitch and roll and 2.0 deg/sec^2 in yaw (Duda, Johnson, & Fill, 2009). When a large attitude rate was commanded, the RCAH attitude control system did not instantaneously command the maximum achievable control power; there was a first-order lag with a time constant of τ =160 milliseconds to reach the maximum attitude acceleration. When large attitude rates were commanded, these low control powers prevented the pilot from reaching the maximum commanded rate, which effectively increased the order of the control system to fourth order (pilot commands attitude acceleration).

The descent engine was assumed to be a fixed-gimbal and had a maximum thrust of 10,000 lbs, with a specific impulse of 300 seconds. Fuel consumption was modeled based on fuel rate needed to hover given the current vehicle total mass, corrected by the cosine of the attitude deviation from vertical. Therefore, as the vehicle tilted further, the fuel usage rate increased. Changing fuel use from vertical acceleration was neglected, since the accelerations are small and typically short-lived. Total fuel mass budgeted for the experimental profile was 50 slugs. The dry vehicle mass was 493 slugs. Fuel slosh or a changing center of mass with fuel consumption was not modeled.

The guidance laws (Billimoria, 2008)were designed to follow a reference trajectory throughout the experimental scenario, and the resultant guidance cues were presented to the subject as errors in pitch, roll, yaw and altitude rate from the desired vehicle state. The reference trajectory was calculated based on the range to target and the projected time until arrival at a point 150 ft above the selected landing point. The initial descent rate (commanded and actual) was -16 ft/sec and decreased linearly to -3 ft/sec until the spacecraft was below 150 ft (as specified by (Billimoria, 2008)) and within 100 ft horizontal range of the designated landing point. Once the 150ft altitude was reached, the vehicle hovered unless it was within the 100ft horizontal range, in which the vehicle would descend at -3ft/s vertical velocity. This range criterion was kept regardless of any redesignations, which commonly resulted in a hover until the vehicle was above the new target. The presented guidance cues were computed as the difference between the guidance computed roll/pitch/yaw angles and the corresponding actual values, and would reflect the changing in the selected aimpoint during runs that required a landing point redesignation. The maximum guidance commanded pitch and roll angles were limited to +/- 45 degrees to limit the effect of large trajectory errors (Billimoria, 2008). The altitude rate guidance was presented as the desired state.

The pitch and roll attitude guidance components provided the pilot with feedback on to the trajectory error. These guidance components were presented as "fly to," which gave the pilot the direction of the pitch and roll commands to null the error. As a result of the tilt of the vehicle from vertical, lateral accelerations were generated to null position errors relative to the reference trajectory in the horizontal plane. The subject was not given explicit feedback on position errors, though current range to target was available in both displays. Vehicle altitude rate control was commanded through the automatic guidance, and the subjects were not responsible for commands in the vertical plane. In the case where the vehicle was not on the reference trajectory, the feedback gain for the lateral acceleration was K_V = 1/1000, and for the vertical speed was K_h = 1/25 (Billimoria, 2008). These gains affected calculation of the guidance components in pitch, roll, and altitude rate. Yaw guidance displayed the relative heading to the selected landing aimpoint; it was not used during the piloting task.

3.22 Achievable Area Calculation

Achievable area was calculated based on the guidance laws described above and the secant method of root finding (for detailed information about the secant method, see Appendix IV). A minimum fuel point was calculated using a 5D linear lookup table. The inputs to the table were north position (ft), east position (ft), north horizontal velocity (ft/s), east horizontal velocity (ft/s), and altitude (ft). Positions were computed by the target relative to the spacecraft. A lookup table was constructed by selecting a range of values for each parameter and running a simulation of the guidance to the target. The fuel consumption to complete each maneuver was noted and entered into a 5D lookup table in the corresponding combination of positions and velocities. This table could be then queried for any combination of the input variables, and the output was the fuel consumption to reach the target given the current positions and velocities. Values were linearly interpolated between the scales chosen in the generation of the lookup table. The minimum fuel point was determined as the north and east target position that resulted in the lowest fuel consumption given the other parameters. Typically this position lies collinear with the current horizontal velocity, and the radial distance outward from the spacecraft increases with magnitude of the horizontal velocity. This method assumes that the vehicle is at the necessary attitude to begin the maneuver to achieve the target point, and therefore does not account for the time needed to rotate the vehicle to achieve the desired attitude.

For each 1° increment around the minimum fuel point, the maximum achievable range was calculated using the lookup table. An initial target point was selected and the north and east positions were entered into the lookup table along with north velocity, east velocity, and altitude. Based on these parameters, the fuel consumption required was identified and compared to the current vehicle fuel. If this difference was less than zero, the target point was incremented closer to the spacecraft (along the same angular ray) and the iteration continued using this new value as per the secant method. If the difference was greater than the selected tolerance of 10kg (0.68 slugs), the point was incremented outwards. If the difference was positive and less than the tolerance, the search loop was terminated and the target position was output as the maximal achievable area. This loop was iterated until a solution was reached within the fuel tolerance.

While it was not used in the experimental setup described below, the achievability calculation can also incorporate elevation information. Digital elevation maps can be included as 2D matrices to find the elevation of the initial (and subsequent) target points of the secant iterations, and use the relative altitude to the target as the search parameter in the 5D lookup table described above.

3.3 Experimental Methods

An experiment was designed to evaluate the effects of the achievability contour display element during simulated approach and terminal descent lunar landing scenarios. The effect was determined by comparing flight performance, situation awareness, and workload measures with the contour display to those with an Apollo-style auditory display. The auditory BINGO callout was selected as the display from the Apollo era most similar to the fuel information provided by the achievability contours. The experiment was designed to support the following hypotheses:

- The achievability contour will result in improved situation awareness and workload as compared to an Apollo-style auditory display
- Changes in control mode and redesignation type will impact the effect of the achievability contour
- The achievability contour will result in improved decision making during LPD

The auditory control display was generated by recording an Apollo astronaut during usability testing. The recordings were trimmed and "start" and "finish" beeps were added to signal the start and end of the auditory message. The messages stated "Draper, X seconds to BINGO", with X being replaced by 60 and 30 seconds as appropriate.

3.31 Experimental Design

An experimental protocol was developed to measure the effects of the achievability contour display element in simulation. Subjects first completed a demographic survey that included information on flight, simulator, and video game experience (see Appendix V for the survey form used). Training was then completed for each subject (see training section below for additional detail). Aside from the two display conditions, two control modes (supervisory vs. manual) and three redesignation types (none, early, late) were determined as independent variables of interest. Supervisory control input the desired attitude guidance value directly into the vehicle dynamics, while the manual control was input as an attitude rate command. The redesignation conditions were implemented as changes in the timing of the appearance of a redesignation command represented as a yellow "X" appearing over the currently designated landing aimpoint. This simulated that the pilot had used out-the-window information to determine that the currently designated target was unacceptable, since the experimental implementation did not include an out the window view. See Figure 18 in Chapter 4 for an example of the redesignation command symbol. For no redesignation (NONE), there was no appearance of the symbol in that trial. For early redesignation (EARLY), the redesignation command appeared 30 seconds into the trial. For late redesignation (LATE), the signal appeared 50 seconds into the trial. The experiment included 32 experimental trials (based on time constraints to keep one simulator session per subject), with 4 initial "throwaway" trials to minimize learning effects. The throwaway trials included 1 NONE, 1 EARLY, and 2 LATE redesignation trials, and used each combination of control mode and display type. A summary experimental matrix is presented in Figure 16 below to show the trials for each condition. The division of trials uses a half redesignation, half no-redesignation format, to ensure sufficient non-redesignation trials as the nominal case. A full experimental matrix as implemented is given in Appendix VI. The nine maps developed (described in section 3.14) were split as evenly as possible over the 32 experimental trials (4 trials with some maps, 3 trials with others). Some maps were repeated over conditions of display type, control mode, or redesignation type, but were not repeated over any single set of the 3 conditions. See Appendix VI for more detail on the maps used by trial.

	Automatic Control			Manual Control		
Redesignation	None	Early	Late	None	Early	Late
Auditory Display	4	2	2	4	2	2
Contour Display	4	2	2	4	2	2

Figure 16. Number of Trials by Experimental Condition

3.32 Measures

Flight parameters were recorded for each trial, including vehicle positions, velocities, attitude, and desired guidance attitude. The recording rate used was 10Hz. Flight performance was measured as the mean square error (MSE) attitude deviation from the guidance cues. This value was calculated for each run, and the tracking MSE was determined as the total MSE not including the periods between a redesignation (or the start of a run) and when the pilot had reacquired the guidance attitude with an attitude (combined pitch and roll) error of less than 10 degrees. This helps to remove the transient error spikes created during the acquisition of the guidance cues for a new target so that the underlying tracking error can be analyzed. Landing parameters were also recorded as the last value prior to 0ft altitude: which included measures of range to target (ft), horizontal velocity (ft/s), attitude deviation from vertical (degrees), and fuel (slugs). Secondary objective workload was measured through the use of a side task. The side task required the subjects to respond to a "COMM" light shown in the lower right hand corner of the landing area display (see Figure 18). A pseudo-random number generator was used to generate a signal (1 or 2) every 15-30 seconds of each trial. The interior of the alert light would turn either blue or green (for a signal of 1=blue or 2=green, respectively), and the subject was instructed to respond as quickly as possible by pressing the associated button on the control joystick without jeopardizing performance on the flight task. The light state was recorded at 10Hz, allowing the response time from when the alert light was first activated to when it was turned off by the subject response. There was no automatic extinguishing with time of the alert light. Each subject had the same number of illuminations each trial. Subjective measures of situation awareness and workload were also taken at the end of each trial. Workload was rated on the Modified Bedford workload scale ((Roscoe & Ellis, 1990), see Appendix VII for the Modified Bedford rating sheet). Situation awareness was rated using the three-dimensional version of the Situation Awareness Rating Technique (SART, see Appendix VIII for SART rating sheet). The currently selected landing aimpoint was recorded at 10Hz to allow for analysis of the LPD decision-making process.

3.33 Subjects

Subjects were recruited from the MIT and Draper Laboratory community (see Appendix IX for the recruitment form used). A total of 10 subjects (7M, 3F) were recruited and run under the protocol described above. Subjects ranged from age 22-32, with an average age of 27. Four subjects reported at least some piloting experience based on a pre-experimental questionnaire (two had pilots' licenses and reported over 50 flight hours of the past 3 years), and four others reported flight simulator experience. All 10 subjects reported some experience with virtual environments. Two subjects indicated red/green colorblindness, but described little trouble in interpreting the displays. There was no report of any trouble reading or interpreting the displays by either colorblind subject. One subject indicated left handedness as defined by the use of the left hand for writing, though the task used only the right hand on the joystick. All subjects signed consent forms to participate in the research, as approved by COUHES (see Appendix X for COUHES approval information). No subjects withdrew from the experiment. Subjects were compensated $10 per hour for participation.

3.34 Training

Training began with the subject reviewing a set of slides outlining the task and equipment (see Appendix XI for the training slides) and finished with a series of training runs covering each experimental condition. Training began with supervisory control in the simplest condition (no side task, no required redesignation, contour display), and progressed by changing one of these conditions in each training run. The same process was then completed for manual control practice runs. Subjects were allowed to repeat any of the training conditions until they were comfortable with their ability to perform the task with that condition. The training protocol resulted in a minimum of 8 training runs, and some subjects requested up to 15 runs. Training runs were performed on a separate training map that was unique from the experimental maps. Subjects were instructed during the slides and simulator training runs to optimize landing parameters at touchdown (low range, low horizontal velocity, near-vertical attitude, high fuel), to follow the flight director needles closely to minimize error, and that the landing points were labeled in preferred order (#1 preferred). In order to maximize fuel, subjects were instructed to use the fuel contours and auditory display to determine the most fuel efficient alternative for redesignation.

3.35 Experimental Procedure

After training, the subjects began the experimental runs. Subjects were informed of the control mode and display type that they would encounter in the trial, before each run. Once each simulation run was started, the experimental displays (PFD on the leftmost display, landing area display to the right) appeared on the two leftmost screens in the simulator (see Figure 17 below). The subject would quickly ascertain the current situation through the displays available, and note the positions of the landing aimpoints. In supervisory control, the subject would continue to monitor the vehicle states and landing aimpoint options while responding to the "COMM" signal (when the signal appeared). In manual control, the subject was additionally responsible for following the flight director needles on the PFD to fly the vehicle towards the initial landing aimpoint. As the scenario progressed, the subjects watched for the appearance of the redesignation signal over the currently designated aimpoint. If this signal was seen, the subject would look at the landing area display to note the current position and achievability of the alternative landing aimpoints, either using the achievability contours or the auditory display. When the subject identified a suitable alternative (usually within a few seconds), they used the trigger on the joystick to cycle the currently designated target to the desired alternate. They would then continue to monitor vehicle systems and respond to the "COMM" signal down to touchdown. In manual control modes, this included guiding the vehicle according to the flight director needles. After touchdown, a score screen appeared, presenting the landing performance of the run to the subject (showing range, horizontal velocity, pitch, roll, and fuel at touchdown). When the subject was ready, they rated the three situation awareness categories (3D SART, scale of 1-7), and the workload of the task (Modified Bedford, scale of 1-10). After the ratings were recorded, the next trial conditions were entered into the simulator and the process was repeated, until all trials were completed.

Figure 17. Simulator Experimental Setup

3.36 Analysis

To address the hypothesis that the contour display has beneficial effects on situation awareness and workload, SART and Modified Bedford ratings were analyzed. SART ratings were analyzed by calculating the average change in each of the three ratings by subject, normalized to ratings with auditory display. This display effect was analyzed across control modes and redesignation types, as well as separately for each combination. A Friedman test was used to analyze the agreement between subjects of the difference between display conditions. Subsets of this data were also analyzed in the same manner to investigate interactions with control mode and redesignation type. Workload was assessed using the Modified Bedford scale and response time to a side task. Modified Bedford ratings were analyzed in the same format as SART ratings. Mean of the logarithm of side task response time for each trial was averaged for each display condition. A mixed-model hierarchical regression was performed to discover the effect sizes and significance of display, control mode, and redesignation type effects. To identify any beneficial effect of the contour display on performance, analysis was conducted on landing performance measures (range, attitude, fuel, and horizontal velocity at touchdown) as well as tracking task performance (through attitude MSE). Landing performance metrics were averaged across trials with similar conditions (display, control mode, redesignation type). Mixed-model hierarchical regression was used to analyze the differences for significance. Mean squared error deviation from attitude guidance was averaged across like conditions and analyzed similar to the landing performance measures.

Changes in decision making were assessed by the timing and selection of an alternate aimpoint during redesignation trials. For the subset of trials for which there was a clear fuel-optimal point at the time of redesignation (by visual inspection), the fraction of fuel optimal selections to total selections was tabulated for each experimental condition. A Friedman test was used to determine the significance of any difference in this ratio based on display type. To show additional behavioral differences in selection, the fraction of times selecting the higher-rated landing aimpoint (#2) to the total times were analyzed in a similar fashion. The number of redesignations for each trial was also recorded (keeping in mind the cyclic selection nature of the inceptor), and differences in number of redesignations was also analyzed using similar regression. Mixed-model hierarchical regression was used to analyze the significance of main effects of control mode, display, redesignation, and cross effects. Comments provided by the subjects during and after the experiment on use of the contour display and the decision making process were noted and inspected for common themes.

4.0 Results

The results section is divided into two parts: the first presents the display design results, and the second presents the results of the subject experiment.

4.1 Display design results

4.11 Initial Design

The initial design for the achievability display concept is included in Figure 18. Like the previous ALHAT display designs, the display is oriented in a top-down view. Hazard areas in red are overlaid on a grayscale topographic map generated by the DEM from the sensor systems. The display is egocentric; the spacecraft symbol remains centered on the screen as the map moves underneath. Two contours are presented: an outer solid yellow contour that shows the achievable limit using all of the fuel remaining, and an inner dotted yellow contour that shows the achievable limit for landing at BINGO fuel remaining. Three landing aimpoints are shown: the primary aimpoint in magenta, and the secondary aimpoints in white. A diamond symbol is used to depict the impact location on the surface if there were no additional control inputs to the vehicle. A timer is included in the upper right corner that shows the estimated time until touchdown. The lower left corner contains scaling information for both horizontal and elevation scaling. The lower right corner has a numeric display of altitude and range to target.

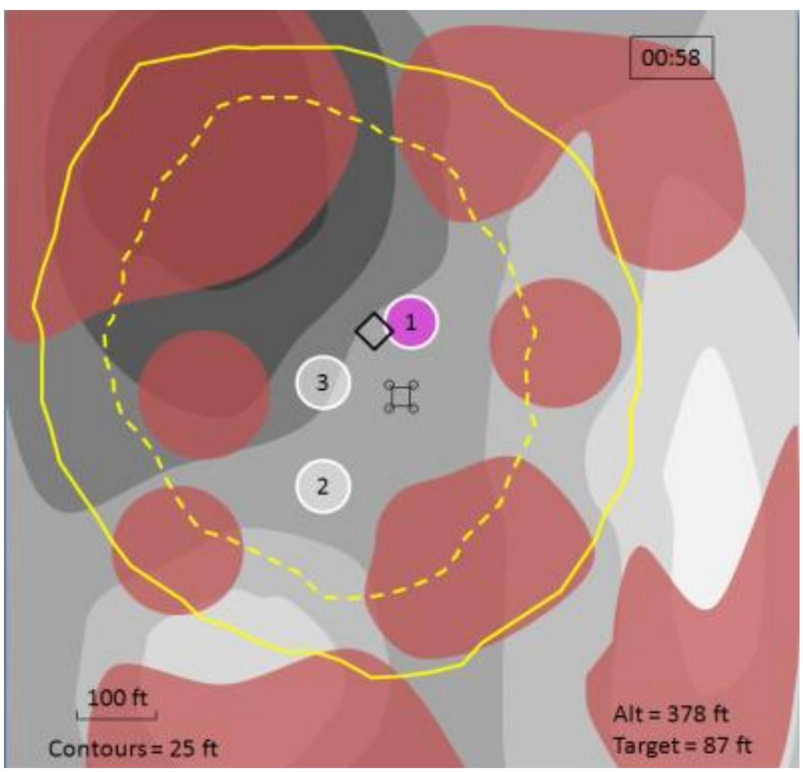


Figure 18. Initial achievability contour display design

4.12 Pluralistic Walkthrough

The feedback during the pluralistic walkthrough with three Apollo astronauts was carefully documented. It included comments about their own experiences and any difficulties during their own landings, their comments on the idea of using the achievability contour display, and specific suggestions for changes to the displays (both PFD and achievability contour) and the simulator. In summary, the astronauts did not feel that spatial disorientation had been a factor in their own landings, and that they had sufficient information for selecting alternate landing aimpoints during their own experience. However, all three commented that the achievability contour display would be very useful to have for future landings to provide confidence in the LPD decision. The CDR felt that the display would definitely be desired by the CDR for future missions, perhaps as part of a HUD. The LMPs indicated that it would be useful to have in a central display, where both astronauts could view it. They suggested that while the CDR maintained control of the vehicle, the LMP could be selecting an alternative, to be confirmed by the CDR. All three indicated that a HUD implementation would be worth consideration in the future. Most of the recommended changes were to the PFD, but there were also several changes indicated for the achievability contour display. For the achievability contour display, the astronauts primarily wanted to see the primary landing aimpoint displayed more prominently, and more focal indications of range to target. This was addressed in the final display as discussed below. A full list of changes (both implemented and yet to be implemented) to both displays is included in Appendix II.

4.13 Final Design

Using input from the usability testing, the final design shown in Figure 19 was developed. The primary landing aimpoint symbology was altered to make it more prominent. A numeric range reading was also added to the primary landing aimpoint. Secondary landing aimpoints were changed to cyan to increase visibility. Text displays of altitude and map scaling were eliminated, as the primary flight display sufficed for altitude, and map scaling information was deemed to not contribute to the landing point selection process. The redesignation symbol (shown as a yellow "x") over the primary landing target is shown in this figure as well. The "COMM" indicator used to assess secondary workload through response time is also included.

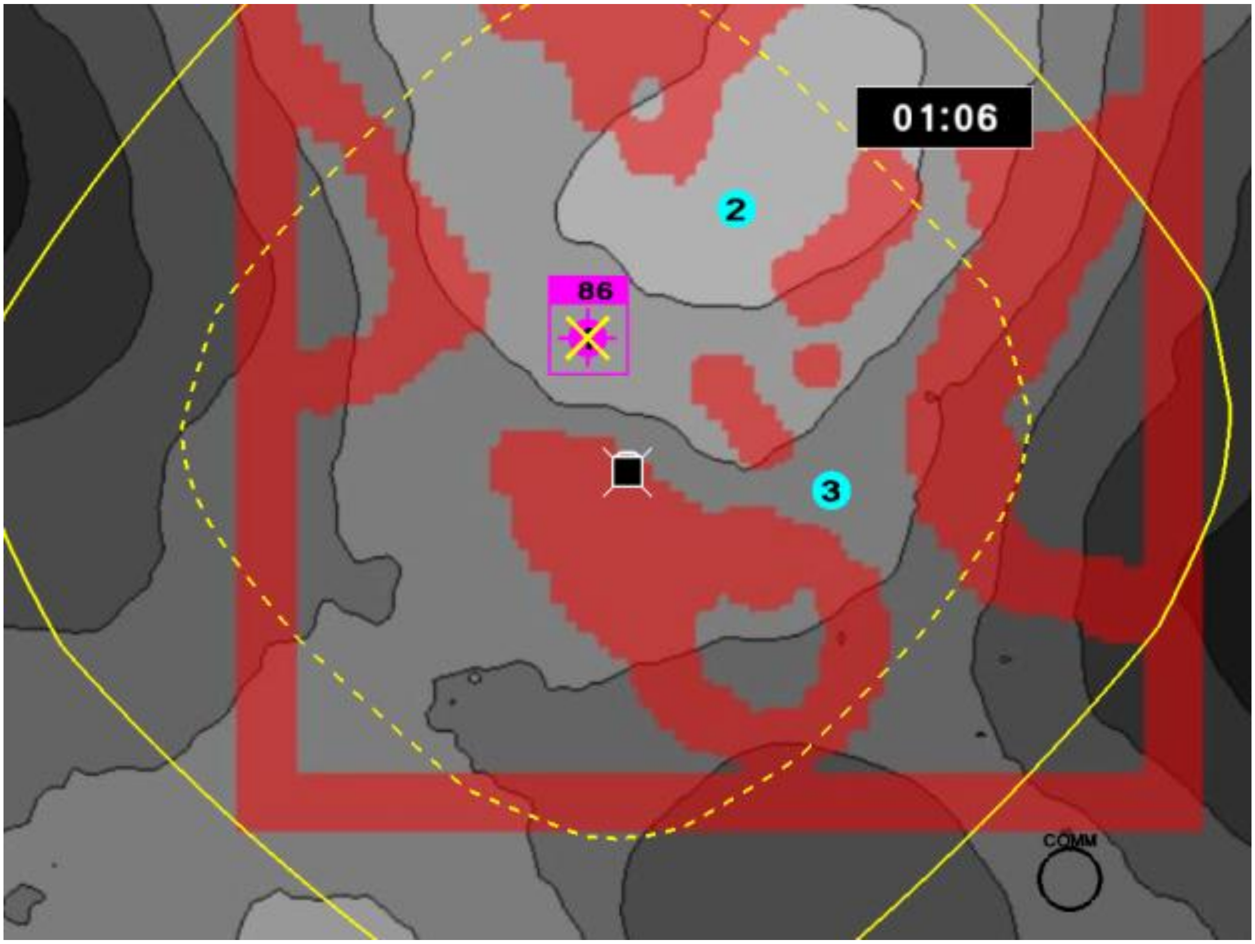


Figure 19. Experimentally implemented achievability contour display

4.2 Experimental Results

Analysis of the experimental results was performed as described in Chapter 3. The achievability contour display demonstrated an effect on the subjective and decision-making behaviors, but had no significant effects on the performance measures. A full discussion of the results of the experiment is presented below.

4.21 Subjective Measures

The subjective measures included the three SART ratings (demand, supply, understanding) as well as the Modified Bedford workload rating. The results of these are presented below, highlighting the effects of the independent variables (display effect, control mode effect, redesignation effect).

4.211 Display Effect

The effect of display (contour minus auditory) on subjective ratings across all subjects, control modes and redesignation types is shown for each subjective measure in Figure 20. The contour display showed no effect on SART demand on attentional resources and supply of attentional resources. An increase in SART understanding of the situation ratings is seen with the use of the achievability contour. Modified

Bedford workload ratings decreased with the achievability contour display. Due to differences between subject rating behavior, the data was analyzed non-parametrically with a Friedman test to look for agreement across subjects. The display effect on SART demand and supply ratings was not found to be significant by Friedman test. The increase in SART understanding and the decrease in Modified Bedford ratings were both found to be significant by Friedman test ($p = 0.003$ and $p = 0.011$, respectively). For graphs of subjective data by dependent variable and comments on the raw data, see Appendix XII.

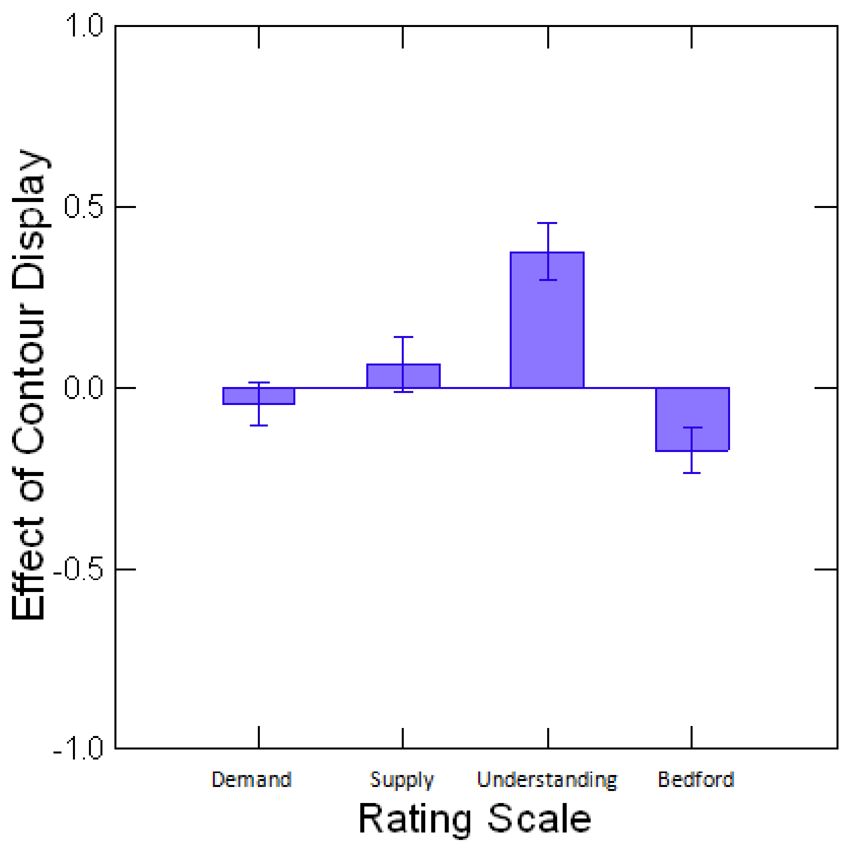


Figure 20. Effect of display (contour – auditory) on each subjective rating scale (avg +/- std err). Positive values indicate higher ratings with the contour display.

4.212 Control Mode Effect

The effect of control mode (manual minus supervisory) on subjective ratings across all subjects, display types and redesignation types is shown for each subjective measure in Figure 21. An increase is seen based on the use of manual control in SART demand and supply ratings, as well as Modified Bedford workload ratings. A slight decrease with manual control is seen on SART understanding of the situation ratings. Similarly to the display effect, the data was analyzed using a Friedman test to identify agreement in ratings across subjects. The increase in SART demand rating was found to be significant by Friedman test ($p = 0.003$). The increase in SART supply was not significant by Friedman test. The slight decrease in SART understanding and the increase in workload ratings were both significant by Friedman test (p = 0.011 for both). For graphs of subjective data by dependent variable and comments on the raw data, see Appendix XII.

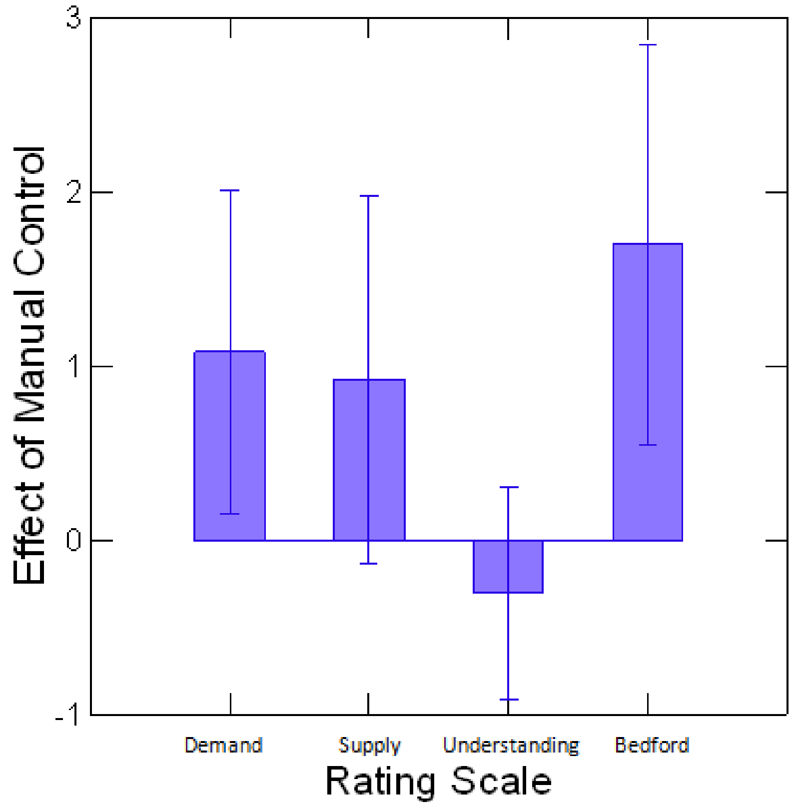


Figure 21. Effect of control mode (manual – supervisory) on each subjective rating scale (avg +/- std err). Positive values indicate higher ratings with manual control.

4.212 Redesignation Effect

The effect of redesignation type (redesignation – no redesignation) on subjective ratings across all subjects, display types and control modes is shown for each subjective measure in Figure 22. An increase is seen based on the requirement of a redesignation in SART demand and supply ratings, as well as Modified Bedford workload ratings. A decrease with redesignation is seen for SART understanding of the situation ratings. As can be seen, the effect of a required redesignation resulted in the same direction change in ratings as the use of manual control. Also, the effect was larger for late redesignations as compared to early for all four subjective rating scales. Similarly to the display effect, the data was analyzed using a Friedman test to identify agreement in ratings across subjects. The increase in SART demand rating was found to be significant for both redesignation types by Friedman test ($p < 0.0005$). There was no significant difference found between the two redesignation types. The increase in SART supply significant by Friedman test for both early and late redesignation as compared to the no redesignation case (p = 0.005, $p < 0.0005$, respectively). There was also a significant increase from the early redesignation to the late redesignation case on SART supply ratings by Friedman test ($p < 0.0005$). The decrease in SART understanding was also significant by Friedman test for both early and late redesignation (p = 0.037, p = 0.002, respectively). The increase in Modified Bedford workload ratings was also significant by Friedman test for both redesignation types (p = 0.001 for early, p < 0.0005 for late). For both SART understanding and workload ratings, there was no significant difference between early and late redesignation types. For graphs of subjective data by dependent variable and comments on the raw data, see Appendix XII.

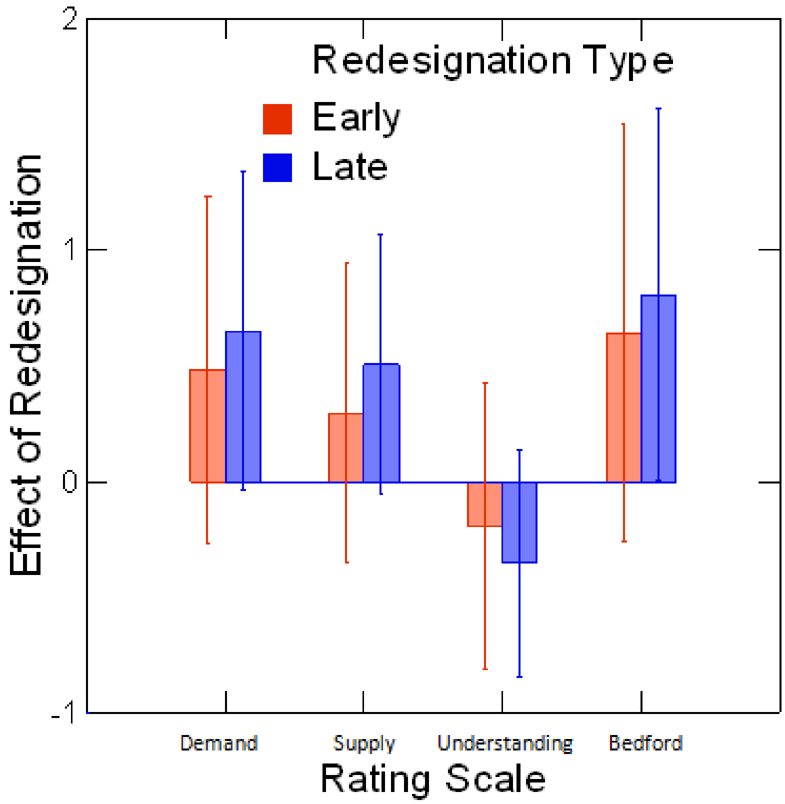


Figure 22. Effect of redesignation type (redesignation – no redesignation) on each subjective rating scale (avg +/- std err). Positive values indicate higher ratings with a required redesignation.

4.22 Performance Measures

Performance measures were analyzed for manual control trials to identify the effect of display and redesignation type. The results are presented below, sorted by measure.

4.221 Touchdown Range

There were no consistent differences in touchdown range performance based on display type (Figure 23) or redesignation type (Figure 24). A mixed model hierarchical regression was constructed, and confirmed the lack of significance of the main effects as well as the cross effect. The lack of sensitivity of this measure is likely due to the choice in vertical guidance algorithm for the experiment. Since the vehicle was programmed not to descend unless it was within 150ft of the guidance target, any extreme outliers in touchdown range would be removed by definition. Therefore, if a pilot lost control of the vehicle, the touchdown range would not suffer as the vehicle would not descend until it was within close range of the target. However, in this scenario, the fuel at touchdown would diminish considerably as the subjects spent time and fuel trying to recover control of the vehicle. For graphs of performance data and comments on the raw data, see Appendix XII.

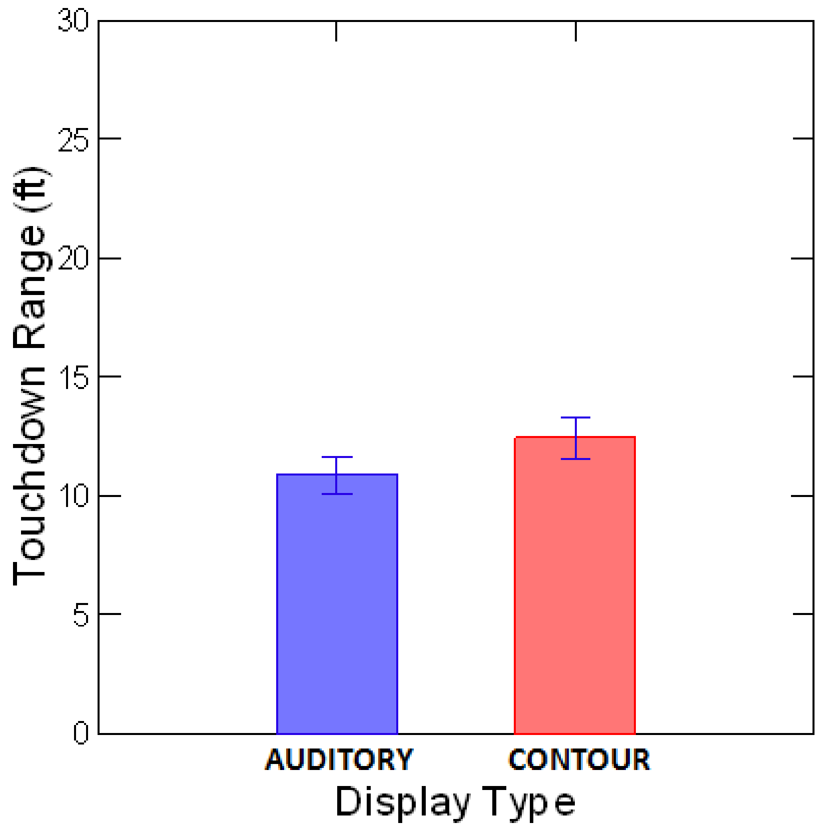


Figure 23. Touchdown range by display type for manual control trials, averaged over subject and redesignation type (avg +/- std err)

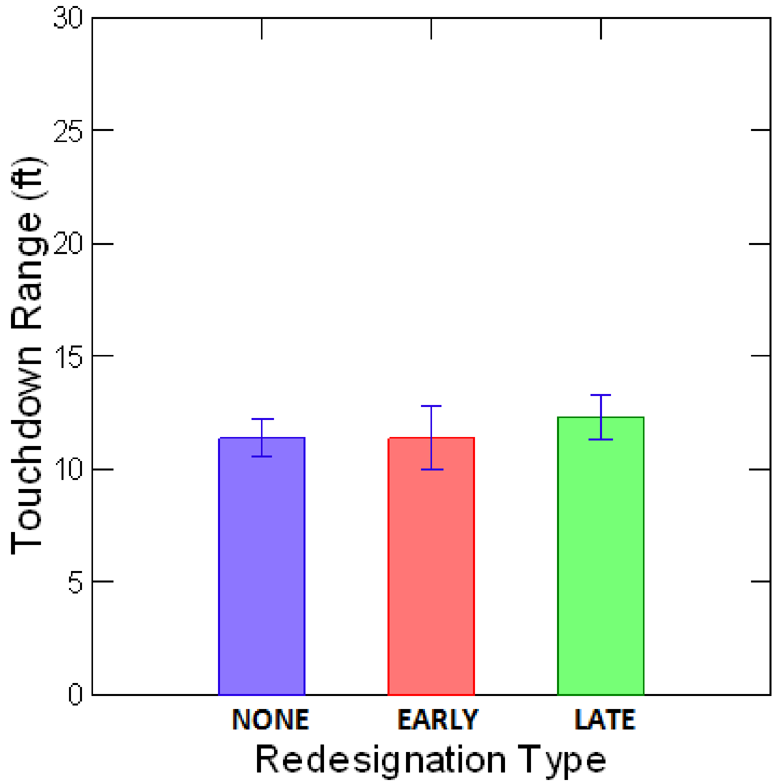


Figure 24. Touchdown range by redesignation type for manual control trials, averaged over subject and display type (avg +/- std err)

4.222 Touchdown Attitude

The touchdown attitude deviation from vertical was measured and analyzed. As with touchdown range, there were no consistent effects with either display type (Figure 25) or redesignation type (Figure 26), confirmed by a mixed model hierarchical regression. It is likely that the sensitivity of touchdown attitude was also reduced by the selection of vertical guidance, since large deviations from vertical attitude would result in a horizontal acceleration, and could move the vehicle outside of the terminal descent range. Therefore, the attitude needed to be kept nearly vertical in order to complete the landing. For graphs of performance data and comments on the raw data, see Appendix XII.

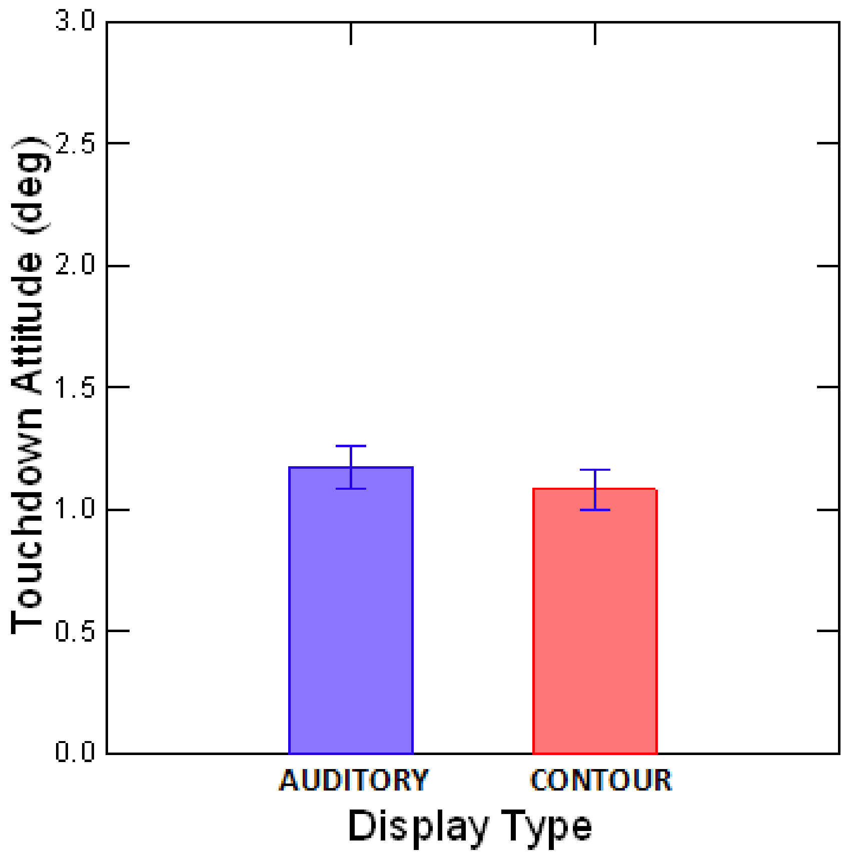


Figure 25. Touchdown attitude by display type for manual control trials, averaged over subject and redesignation type (avg +/- std err)

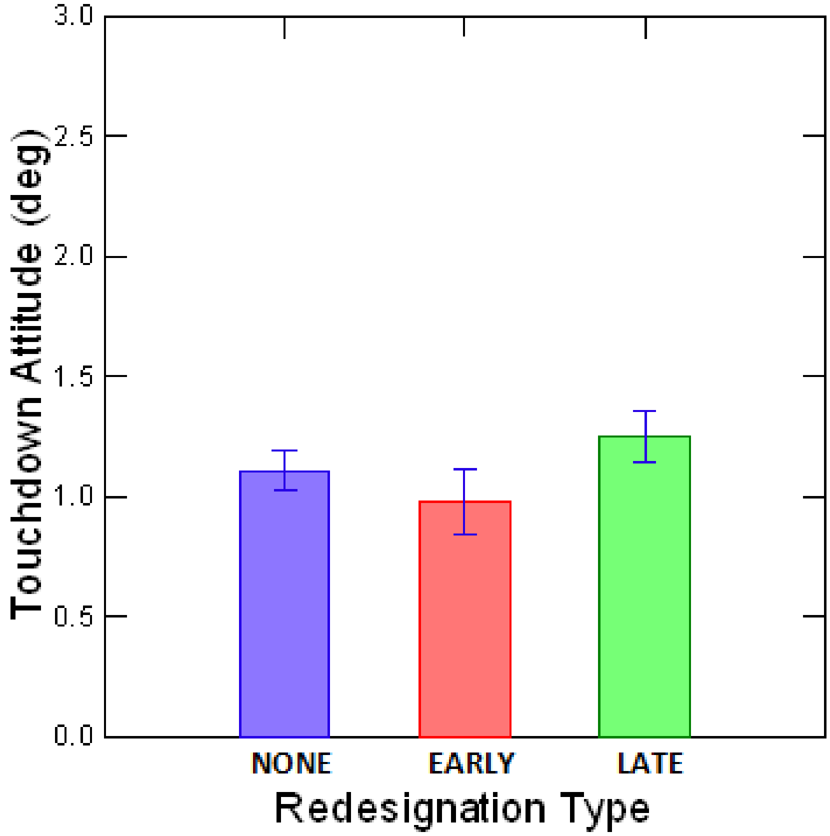


Figure 26. Touchdown attitude by redesignation type for manual control trials, averaged over subject and display type (avg +/- std err)

4.223 Touchdown Horizontal Velocity

As with touchdown range and attitude, touchdown horizontal velocity showed no significant differences based on display type (Figure 27) or redesignation type (Figure 28) with a mixed model hierarchical regression. The same issues with the vertical guidance used as described above apply to this measure, since high horizontal velocity would likely result in large range deviations from the target. For graphs of performance data and comments on the raw data, see Appendix XII.

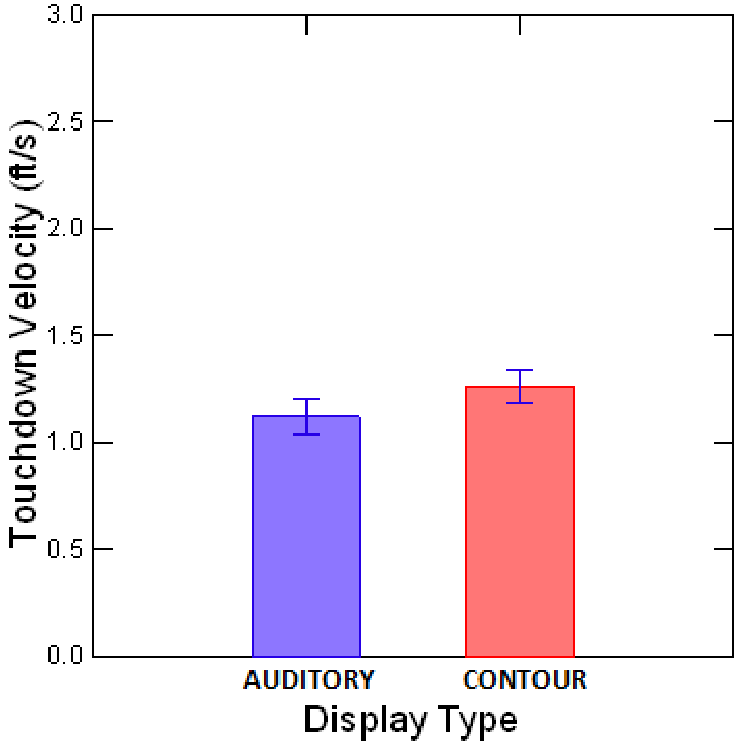


Figure 27. Touchdown velocity by display type for manual control trials, averaged over subject and redesignation type (avg +/- std err)

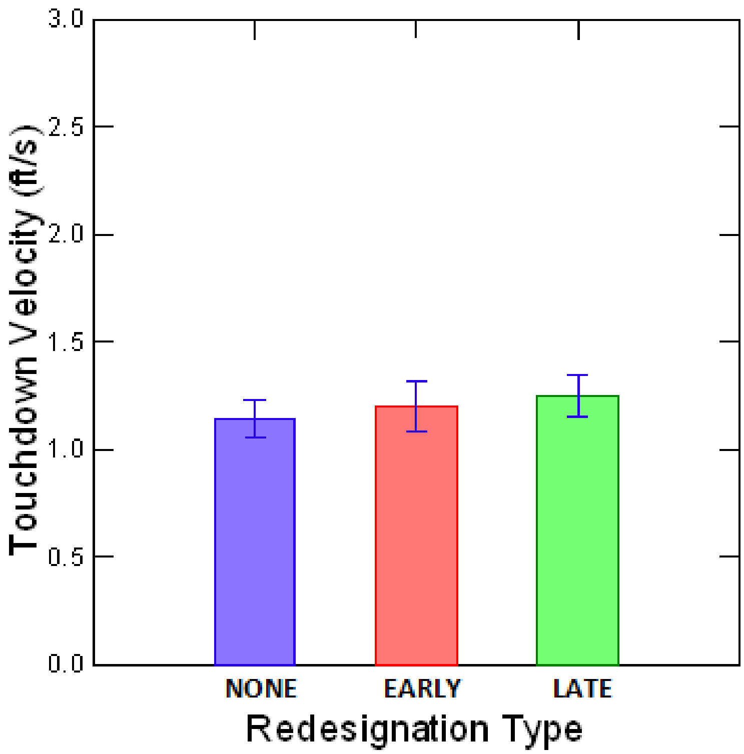


Figure 28. Touchdown velocity by redesignation type for manual control trials, averaged over subject and display type (avg +/- std err)

4.224 Touchdown Fuel

A decrease in touchdown fuel is seen with the use of the contour display (Figure 29). As might be expected, the effect of redesignation is significant and graduated in the expected direction, (no, early, late) redesignation in decreasing order. A mixed model hierarchical regression was analyzed against main effects of display and redesignation. The cross effect was also tested, but was determined to not contribute to the model fit. The results of the model construction are listed below:

Variable	Estimate	Standard Error	Z	p-value
Subject	614.163	17.064	35.993	0.000
Auditory Display	32.111	13.910	2.308	0.021
No Redesignation	262.747	18.769	13.999	0.000
Early Redesignation	-12.830	22.188	-0.578	0.563
Late Redesignation	-249.917	20.239	-12.348	0.000

Table 1. Mixed Model Hierarchical Regression Results for Touchdown Fuel

These results show that subjects land with significantly less fuel (-32.111) below the overall average when they are using the achievability contour display. We expected the opposite, since that display was intended to make them more aware of fuel usage. This could indicate that the subjects were more confident in selecting a higher ranked point that is father away with the fuel contours. It also suggests that the subjects may have been more conservative in selection with respect to fuel when using the auditory display. This result is discussed further in Chapter 5. For graphs of performance data and comments on the raw data, see Appendix XII.

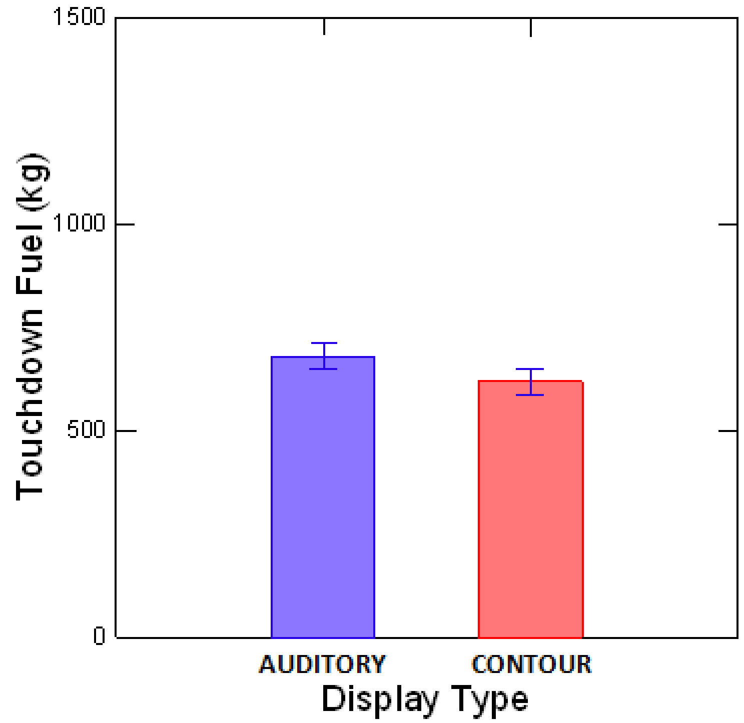


Figure 29. Touchdown fuel by display type for manual control trials, averaged over subject and redesignation type (avg +/- std err)

The maps tested in the experiment differ in the location of the initial landing target and of the landing alternatives, and those features have an effect on fuel remaining at touchdown. Figures 45a,b,c, show respectively, the fuel remaining at touchdown for no-redesignation, early redesignation, and late redesignation trials. Within each plot, the fuel remaining (averaged over all subjects and display conditions) is plotted against map type. The starting vehicle position is the same on every map, but the targets (landing aimpoints) are different. The initial target for map 4, for example, is farther from the starting vehicle position than in map 5.

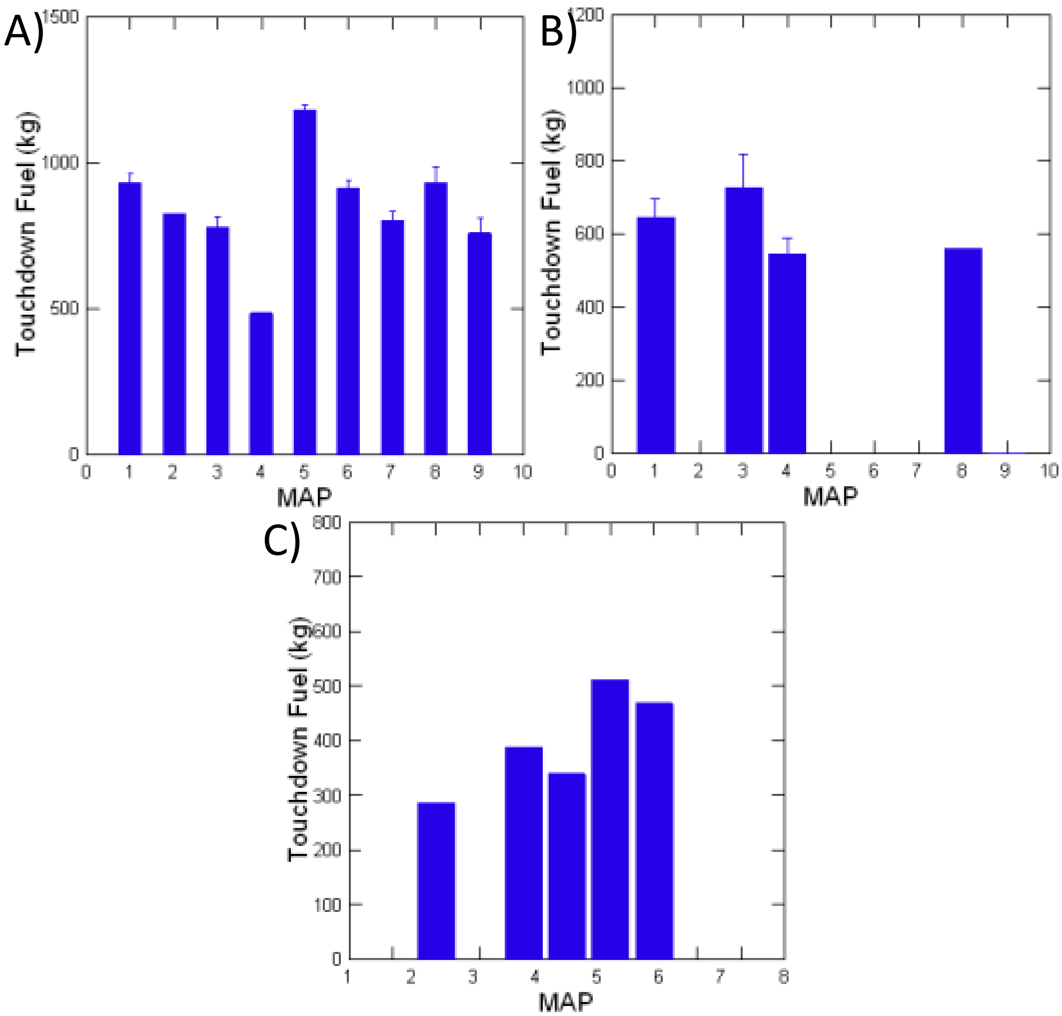


Figure 30a,b,c. Touchdown fuel by map for each redesignation type. Trials with (no, early, late) redesignation are shown in (a, b, c), respectively. Some map configurations were omitted from the experiment.

4.225 Tracking Mean Square Error (MSE)

The quality of flight performance was measured by the mean square deviation (error) between the actual vehicle and the guidance recommended combined pitch and roll attitude. The redesignation portions of the trajectory (as defined in section 3.32) were removed to eliminate transients and to allow coherent comparisons to be made. This is discussed in Chapter 3. Attitude MSE is shown below by display type (Figure 31) and redesignation type (Figure 32). For graphs of performance data and comments on the raw data, see Appendix XII.

A mixed model hierarchical regression was constructed with main effects of display and redesignation. The cross effect was also tested, but was determined to not contribute to the model fit. Results of the model construction are listed below:

Variable	Estimate	Standard Error	Z	p-value
Subject	83.293	13.252	6.285	0.000
Auditory Display	4.424	7.736	0.572	0.567
No Redesignation	-49.854	10.439	-4.776	0.000
Early Redesignation	40.433	12.344	3.275	0.001
Late Redesignation	9.421	11.266	0.836	0.403

Table 2. Mixed Model Hierarchical Regression Results for MSE

The model indicates that the achievability contour display had no influence on flight performance, but the redesignation type does. There are significant differences between all of the redesignation types, with no redesignation associated with the lowest MSE, late redesignation with the middle MSE, and early redesignation with the highest MSE. This suggests that for an increased MSE, the subject ignores the flight task while making the redesignation decision. An early redesignation would allow for more available time to make the decision, and is supported by the number of redesignations analysis below in the decision-making behavior analysis.

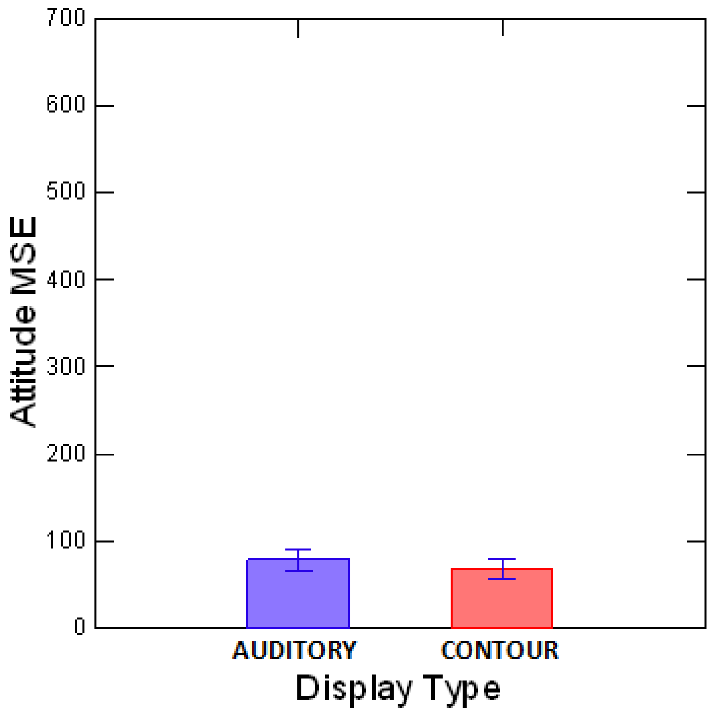


Figure 31. Attitude MSE by display type for manual control trials, averaged over subject and redesignation type (avg +/- std err)

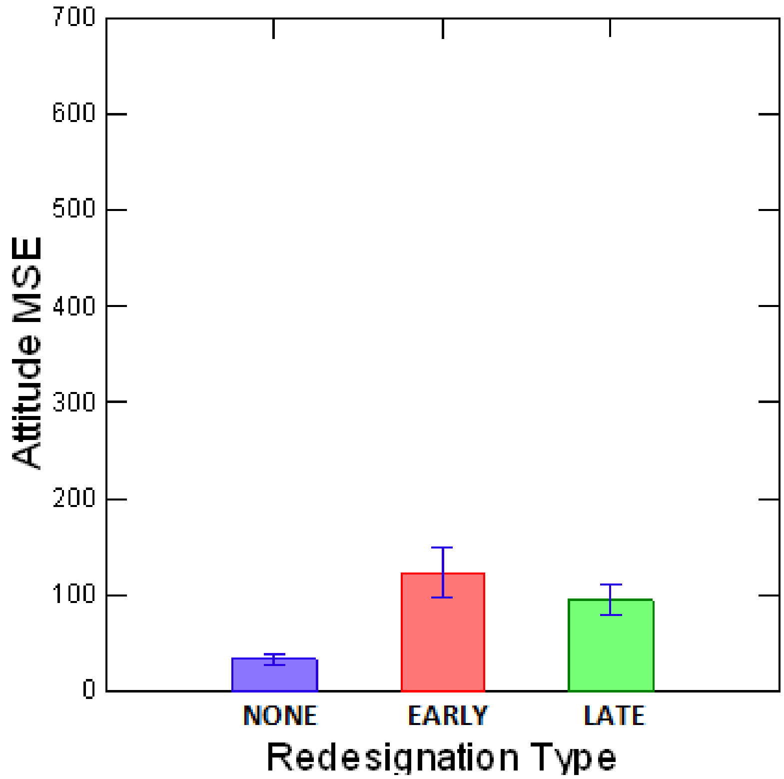


Figure 32. Attitude MSE by redesignation type for manual control trials, averaged over subject and display type (avg +/- std err)

4.226 Secondary Workload

Secondary workload was measured by the response time to a communications signal as described in Chapter 3. Approximately 10 signals were given to the subject during each trial, and the logarithms of the response times were averaged to determine the response time metric. There was no observable effect of display type (Figure 33) or control mode (Figure 34). This indicates that the chosen side task was not sensitive to workload changes based on control mode. Future experiments should implement a more sensitive measure of secondary workload, and this is discussed in further detail in Chapter 5. Response times based on redesignation type are graphed in Figure 35. There is a slight increase in response time from “none” to “early” to “late” cases. For graphs of performance data and comments on the raw data, see Appendix XII. A mixed model hierarchical regression was performed to analyze the significance of the main effects of redesignation type, control mode, and display type. The cross terms of each (including the cross of all three) were also tested, but were determined to not contribute to the model fit. The results are presented below:

Variable	Estimate	Standard Error	Z	p-value
Subject	-0.030	0.060	-0.502	0.616
Auditory Display	0.004	0.008	0.466	0.641
No Redesignation	-0.018	0.011	-1.618	0.106
Early Redesignation	-0.011	0.013	-0.857	0.391
Late Redesignation	0.029	0.013	2.310	0.021
Automatic Control	-0.001	0.008	-0.176	0.860

Table 3. Mixed Model Hierarchical Regression Results for log(side task response time)

The model confirms the lack of an effect based on display type and control mode, and indicates that late redesignations are significantly higher than the no redesignation and early redesignation cases. Therefore, only the high time pressure of the late redesignations had an effect on side task response time.

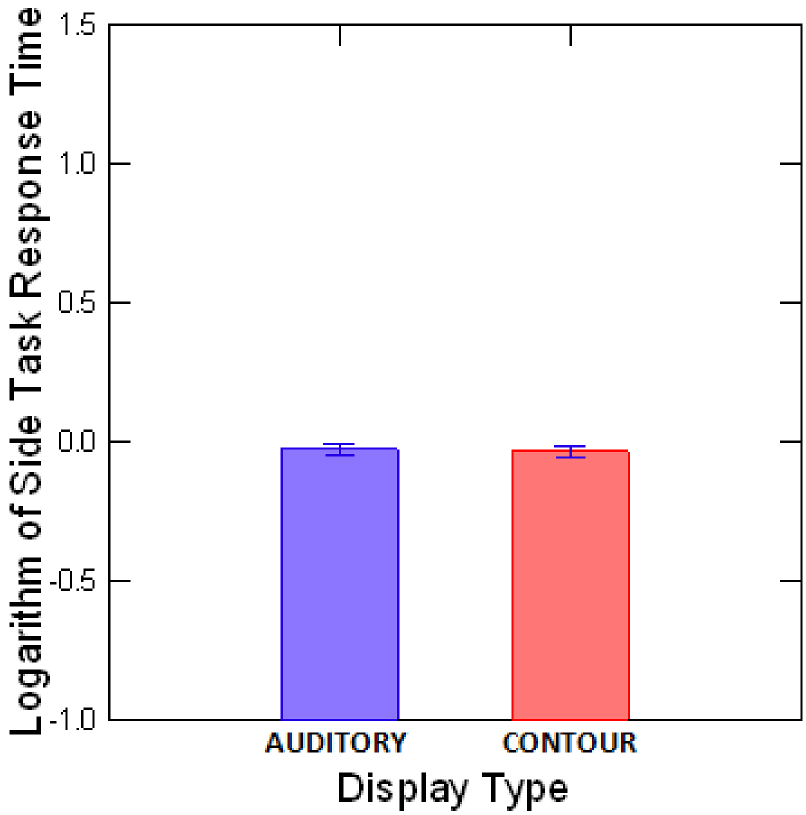


Figure 33. Log(side task response time) by display type averaged over subject, control mode, and redesignation type (avg +/- std err)

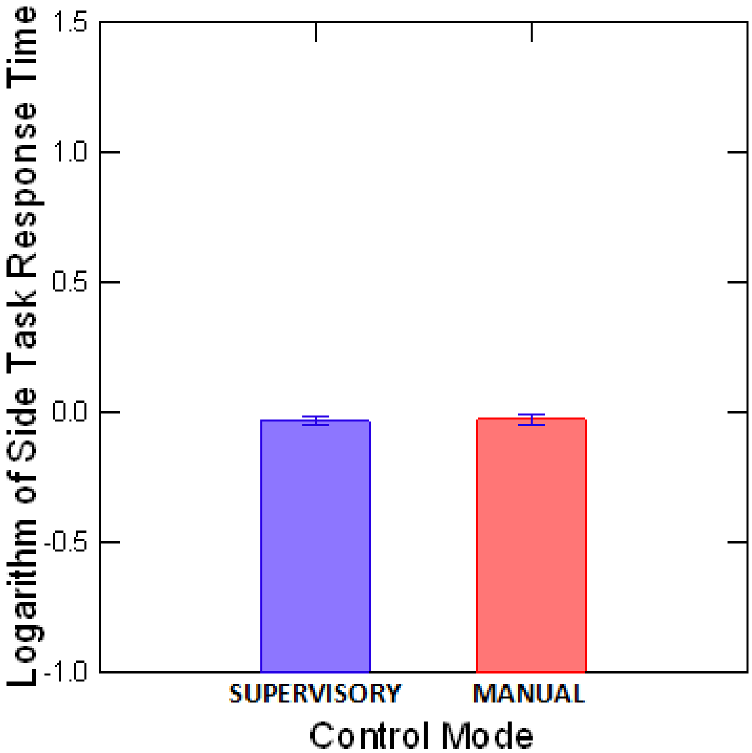


Figure 34. Log(side task response time) by control mode averaged over subject, display type, and redesignation type (avg +/- std err)

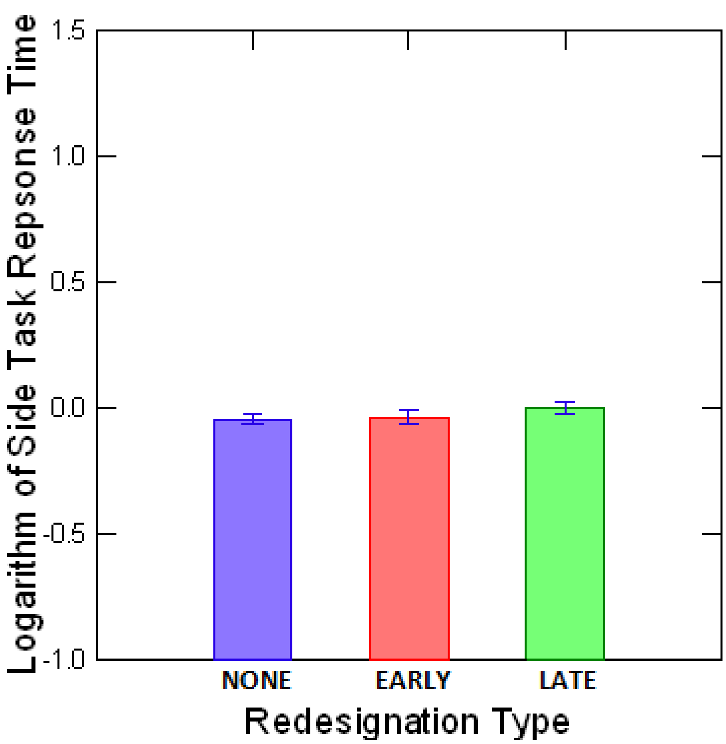


Figure 35. Log(side task response time) by redesignation type averaged over subject, display type, and control mode (avg +/- std err)

4.23 Decision-Making Behavior Results

4.231 Fuel Optimal Ratio

Using the fuel contour display, it is sometimes clear that one landing aimpoint is more fuel efficient (optimal) than the other. For the trials that included such a clear fuel optimal point at the time of a required redesignation, we calculated the ratio of the number of times that the subject selected the fuel optimal point to the total number of applicable trials. In other words, a higher ratio indicates that the subject more often selected a better landing point in terms of fuel use. To be classified as one of these trials, at the time of redesignation one of the landing points needed to be at least 0.25 inches (at the experimental display resolution) closer to the center of the contours, as measured from the contour edge. Note that this ratio is not related to the fuel at landing, but the number of times that the subject selected the landing point that *should* result in the highest fuel at touchdown. This "fuel optimal" ratio is plotted by subject in Figure 36. The differences between subjects can be explained as the combined effect of redesignation timing, perception of difficulty, and interpretation of goals. There were several maps in which the landing alternative favored by fuel optimality changed close to the time of the redesignation command. For example, the fuel optimal landing target immediately after the redesignation command might be different from the one that is fuel optimal 5 seconds later.

Perceived difficulty also played a role in selection. Several subjects reported that they felt more comfortable redesignating downrange in manual mode to simplify the control task further on. This sometimes resulted in the selection of the less-optimal fuel aimpoint. Subjects also interpreted the goals differently. They were instructed to optimize fuel, and that the landing points were given in order of preference according to the automated system ratings (#1 is “preferred”). In some cases they chose the “preferred” alternative, and in other cases the fuel-optimal alternative. This difficulty is prominent when the #3 (for preference) alternative happens to be the fuel optimal one. This emphasizes the complex decision-making required in a late-stage redesignation. Further experiments may elucidate the tradeoff of fuel cost and landing point terrain safety (as given by the automated system ratings), and are discussed in Chapter 5.

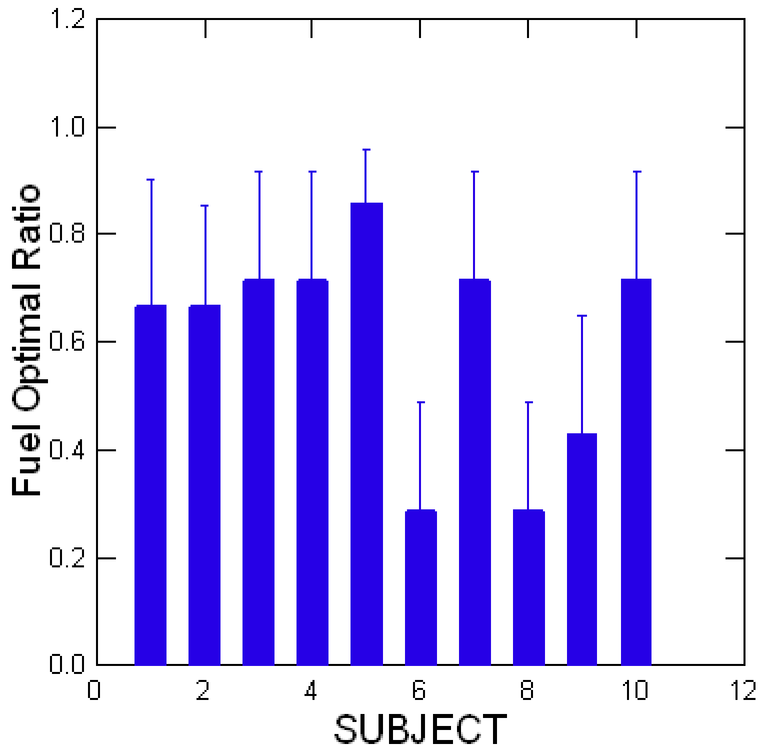


Figure 36. Fuel Optimal Ratio by subject across all applicable conditions (+/- standard error)

Fuel optimal ratio showed a marked decrease with the contour display (Figure 37), but this was not significant by Friedman test. Despite the lack of significance, this decrease is noticeable enough to merit further investigation, and implies that there may be some interaction of the contours with the LPD decision-making process. Several subjects reported using the achievability contours to improve the assurance that they would reach an alternative LAP rather than by fuel optimality. In effect, they were not optimizing fuel, but rather their own confidence that they could meet a computer-preferred landing aimpoint. There were no cases, however, in which subjects chose an aimpoint that was inferior both in fuel consumption and by automated system rating when they had a contour display. By contrast, when they had an auditory display they were less likely to choose the automated system-preferred aimpoint when it had inferior fuel consumption. Further implications of this decision-making process are discussed in Chapter 5. For graphs of performance data and comments on the raw data, see Appendix XII.

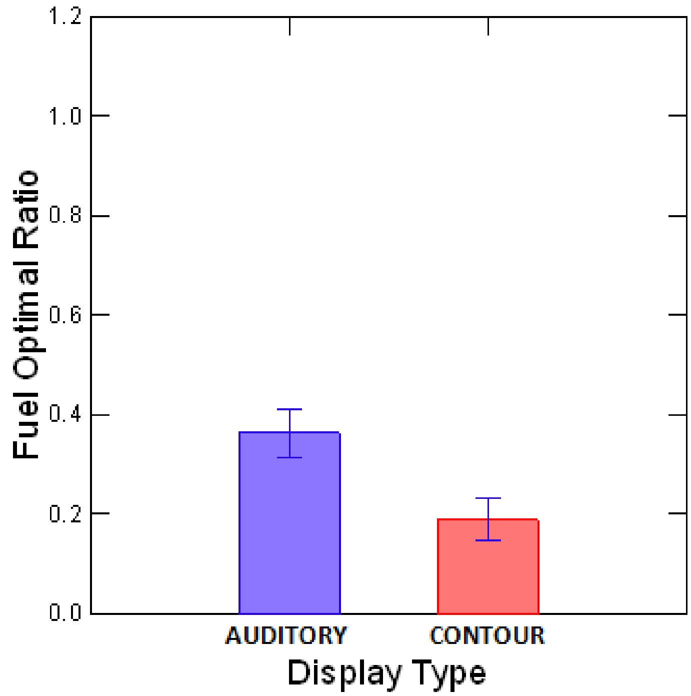


Figure 37. Fuel optimal ratio by display type, averaged across subject, control mode, and redesignation type (avg +/- std err)

There was a slight decrease in fuel optimal ratio with manual control compared to supervisory control (Figure 38), but this was not significant by Friedman test. This decrease could be indicative of subjects being uncomfortable making severe redesignations in order to achieve the fuel optimal point when in manual control. For example, if at the time of the redesignation the fuel optimal alternative is in the opposite direction from the current horizontal velocity, an extreme attitude maneuver would be needed to reverse direction. In these cases, the subjects may have been more comfortable commanding these redesignations when in supervisory control, which suggests a high level of trust in the automation. This concept is further supported when viewing the effects of landing location and control mode on the fuel optimal ratio are graphed by map in Figure 39 for the applicable conditions (also reference the images of the maps in Appendix III). The redesignation trials on map 6 had a fuel optimal point that was further from the spacecraft location than the less optimal point, and these trials used the auditory display. This suggests that in manual mode, the subjects merely selected the closest landing aimpoint, rather than the fuel optimal one. The selection of the closest alternative in manual mode with the auditory display is supported by the differences in Figure 58. In map 8, the auditory display was used and the fuel optimal alternative was the one closer to the spacecraft location at the time of redesignation. In map 9, the fuel optimal location was further from the current spacecraft location at the time of redesignation, but the subjects had access to the achievability contour display. This suggests that subjects were using the simple judgment of proximity to the spacecraft in the selection of alternates, particularly in the absence of the contour display. It is worth noting that proximity to the spacecraft does not always correspond to the lowest fuel cost, and thus could represent a dangerous pilot decision in an actual lunar landing. Subjects were not instructed specifically to this danger.

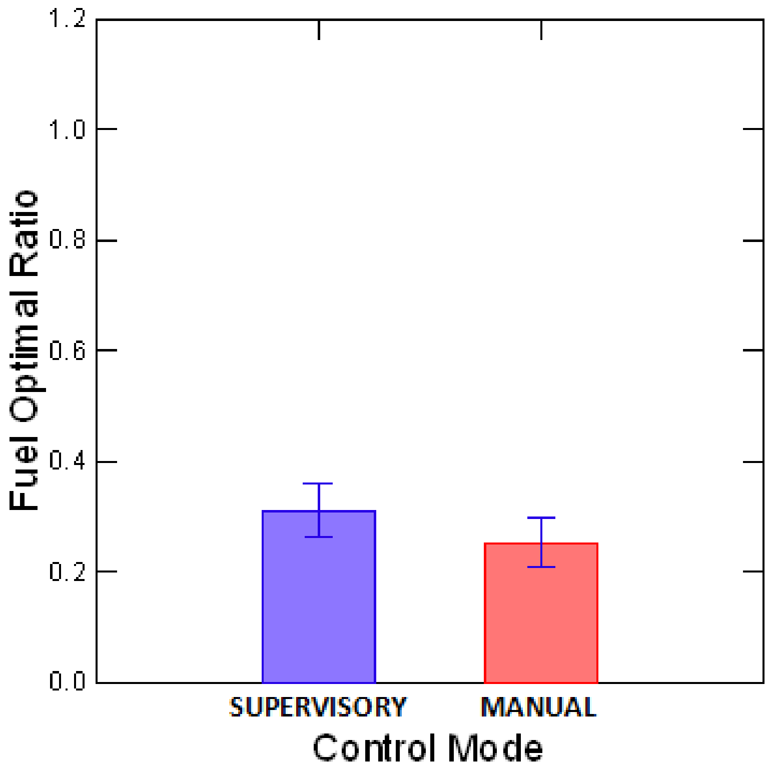


Figure 38. Fuel optimal ratio by control mode, averaged across subject, display type, and redesignation type (avg +/- std err)

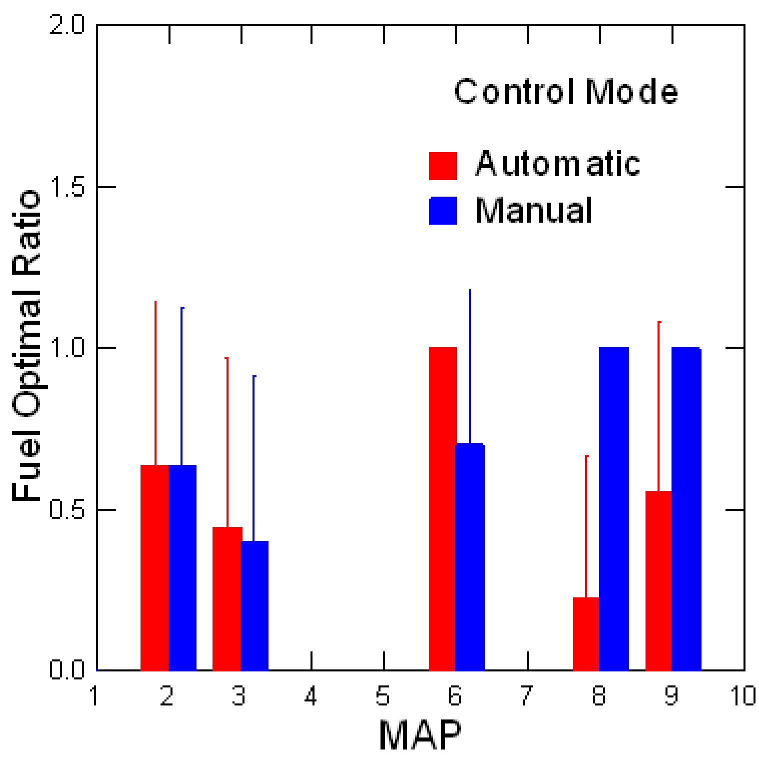


Figure 39. Effect of map and control mode on fuel optimal ratio averaged over subjects (avg +/- std err)

Fuel optimal ratio is graphed by redesignation type in Figure 40. An increase in fuel optimal ratio is observed for late redesignations as compared to early redesignations (note that only trials with required redesignations and clear fuel optimal alternatives were included). This follows the logic that under the lower fuel margin conditions of a late redesignation, the subjects must redesignate more conservatively with respect to fuel. However, this effect was (barely) not significant (Friedman test, p = 0.058).

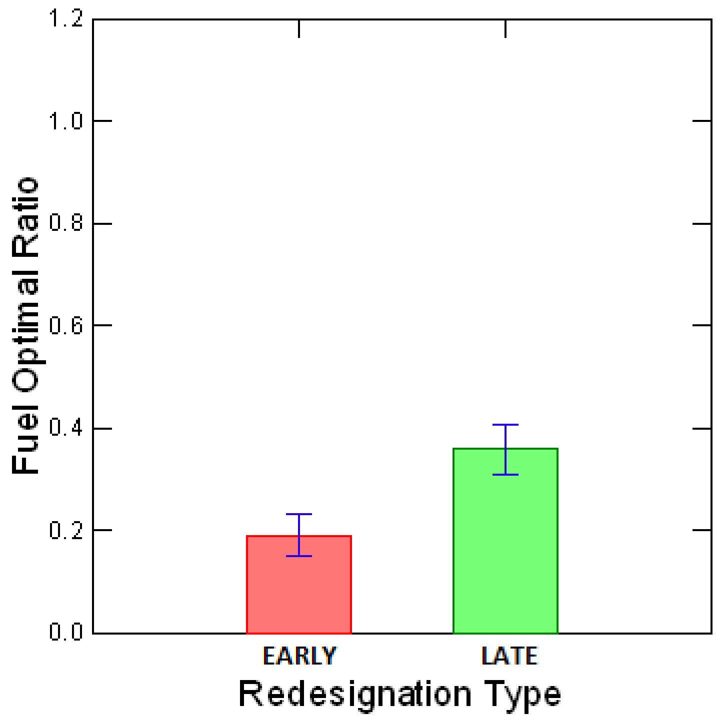


Figure 40. Fuel optimal ratio by redesignation type, averaged across subject, control mode, and display type (avg +/- std err)

4.232 Number of Redesignations

For required redesignation trials, the number of redesignations was defined as the number of times the landing aimpoint was changed, excluding those redesignations that lasted less than 1 second before another redesignation occurred. This exclusion suppressed accidental redesignations and redesignations made to "cycle" through to a different alternate (due to the cyclic selection nature of the experimental landing point designation process). A number of redesignations greater than 1 indicates that the subject changed his/her mind after making the initial redesignation.

There were no observable differences by display in number of redesignations (Figure 41). For graphs of performance data and comments on the raw data, see Appendix XII. A mixed model hierarchical regression was performed with subject as a random effect and main effects of control mode, redesignation type, and display type, and the cross effect of redesignation type and display type. The results of the model are shown below. The main effects were not significant, but the cross effect of redesignation type and display type was significant (p = 0.028): there were more redesignations than average with the auditory display and early redesignation (Figure 42). That combination of conditions is particularly conducive to indecision: there is more time and fuel margin for decision-making in an early redesignation case, and the subject does not have immediate knowledge of the relative fuel cost of alternatives because he/she does not have achievability contours.

Variable	Estimate	Standard Error	Z	p-value
Subject	1.620	0.083	19.604	0.000
Automatic Control	-0.022	0.067	-0.330	0.742
Auditory Display	-0.073	0.067	-1.086	0.278
Early Redesignation	0.104	0.067	1.544	0.123
Redesignation x Display	0.147	0.067	2.199	0.028

Table 4. Mixed Model Hierarchical Regression Results for Number of Redesignations

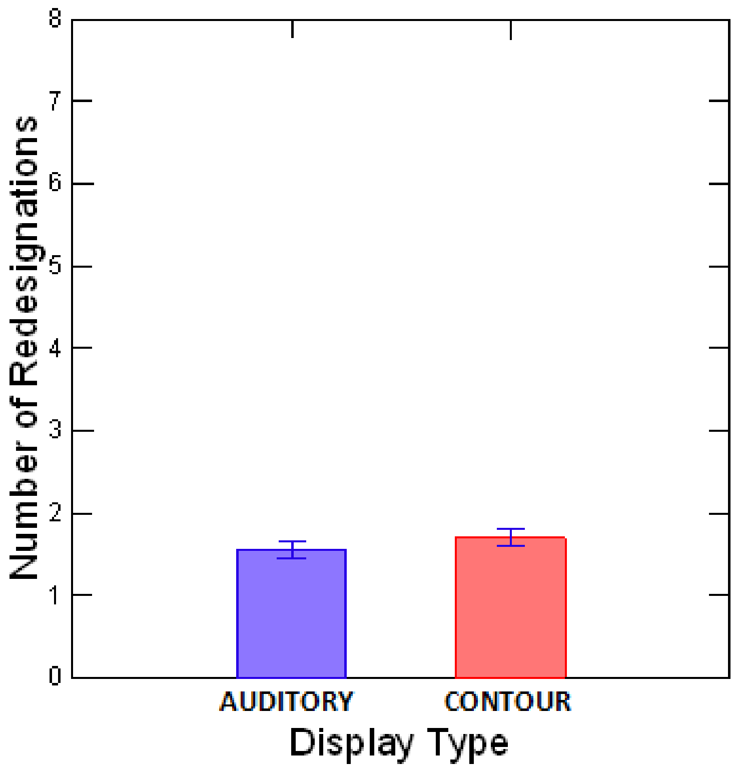


Figure 41. Number of redesignations by display type, averaged across subject, control mode, and redesignation type (avg +/- std err)

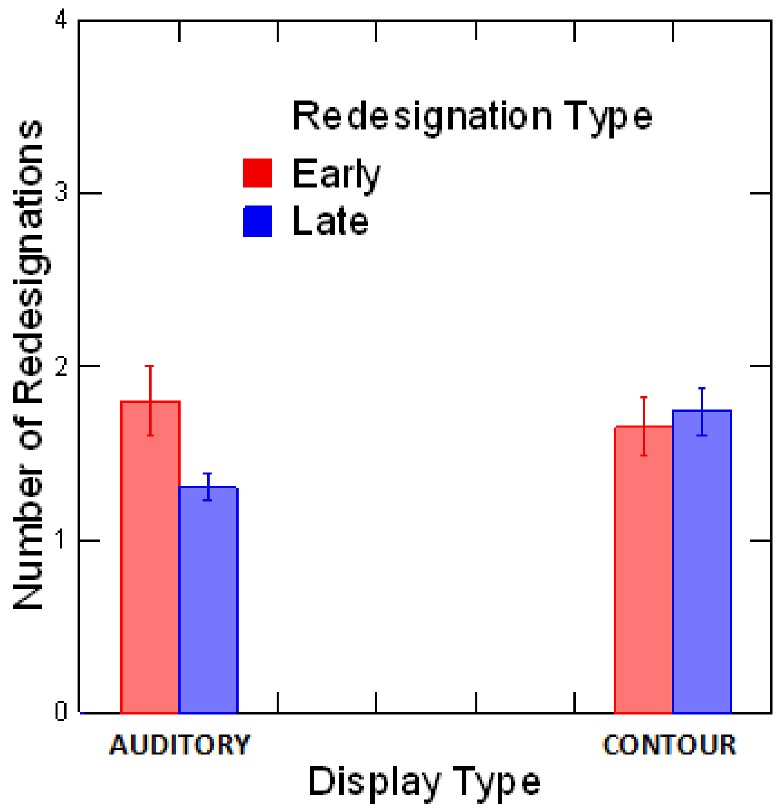


Figure 42. Number of redesignations by display type and redesignation type, averaged across subject and control mode (avg +/- std err)

The locations of landing alternatives—which differs from map to map—can have an effect on the ambiguity in the redesignation options. The number of redesignations, plotted against map type in Figure 61, is roughly the same for all types. Map 6 included some ambiguity (based on fuel usage), but the fuel optimal point was downrange of the initial target. A preferential selection of downrange targets could have reduced the number of times that the subjects changed their mind. In map 5, there was no ambiguity in landing alternate selection, and therefore it is plausible that subjects would select the obvious best alternate and stay with it.

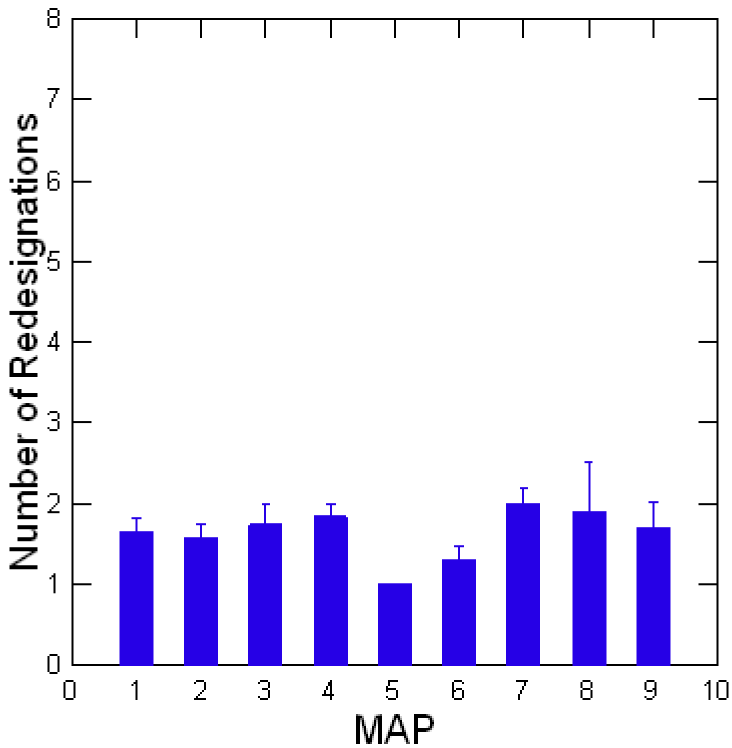


Figure 43. Number of redesignations by map averaged over all redesignation trials (avg +/- std err)

4.232 Experience

It was noted for several of the touchdown performance measures (range, attitude, horizontal velocity), that several subjects (subjects 1 and 10, see Appendix XII) consistently performed better than the other subjects. Upon further investigation, these subjects had the greatest flight experience as reported on the pre-experimental questionnaire. Therefore, the data was analyzed for effects of flight and simulator experience. Three levels of experience were selected based on the responses to the questionnaire: pilot (licensed, 2 subjects), simulation (previous experience with lunar landing simulation, 6 subjects), or none (2 subjects). An ANOVA model was constructed for each metric with experience as a factor, and Tukey pairwise comparisons were performed to identify differences between experience levels. Licensed pilots performed significantly better than other subjects on touchdown range ($F(2,177) = 13.016$, $p<0.0005$), velocity ($F(2,177) = 9.898$, $p<0.0005$), and attitude ($F(2,177) = 11.228$, $p<0.0005$) (see Figure 44).

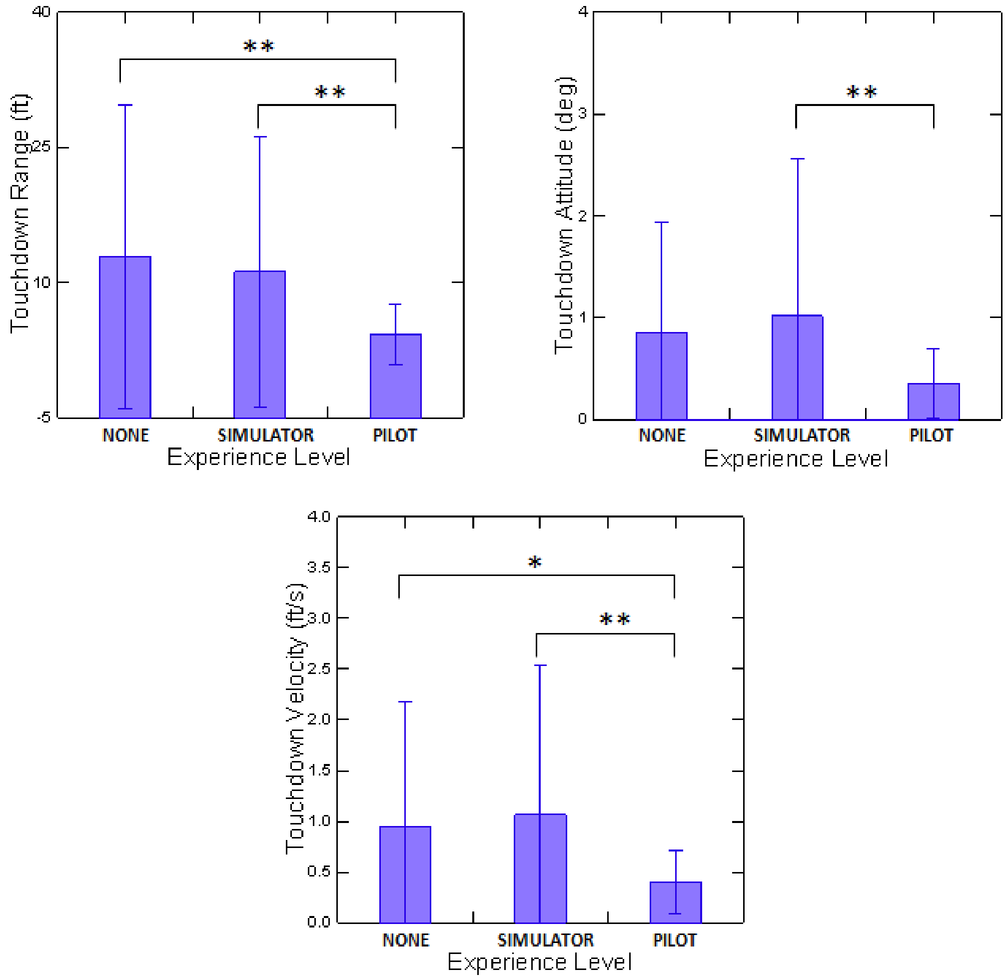


Figure 44. Effect of experience level on touchdown range, touchdown attitude, and touchdown velocity in manual control trials (avg +/- std err, * = significant at p = 0.05, ** = significant at p = 0.001)

5.0 Discussion and Conclusions

5.1 Display Design and Evaluation

The display design process provided for the creation of a functional display. The GDTA allowed for an overarching view of the LPD task and the decisions that needed to be made during this task. It was this task and information analysis that led to the creation of the achievability contours, and should be included in further display development. The pluralistic walkthrough with Apollo astronauts provided immense feedback and ideas for both the displays and the simulation. The astronauts indicated that the display would be very useful in future missions, particularly as a decision support tool. Some, but not all, of the comments and suggestions were implemented in the experiment, and a full list is provided in Appendix II to support future development. The inclusion of this type of usability testing is highly recommended to evaluate future design iterations.

5.2 Display Effect

The developed achievability contour display resulted in improved subjective ratings of situation awareness and workload, and had significant effects on decision-making behavior during simulated lunar landing scenarios. The improvement in subjective ratings suggests that the contours could help astronauts in the landing point designation task. However, the reduced subjective workload ratings were not duplicated in the objective secondary workload measurements. Given that the secondary workload measurements could also not detect any effect of control mode, it is apparent that the measure used in this experiment was not sufficiently sensitive to detect changes in workload. This was compounded by reports from subjects on the overall ease of the task. Future experiments should increase the sensitivity of the secondary workload measure and increase the workload of the overall task. An experiment in a recent thesis created a low color contrast secondary task indicator, such that the subject needed to focus directly on the indicator to be able to discern the presence of a signal (Hainley, 2010). Results of this implementation gave more sensitive results, and could be used to further evaluate the achievability contour display. Workload on the overall task could be increased by requiring the subject to control additional aspects of vehicle motion, such as descent rate or yaw attitude.

The achievability contour also had an effect on the selection of the fuel optimal landing aimpoint. The decrease in the fuel optimal ratio seen in the data was not anticipated, and is the opposite of the expected result. Subjects reported using the fuel information contained in the achievability contour display to improve their confidence in the landing aimpoint selection. During most of the trials included in the experiment, both landing aimpoints were achievable at the time of redesignation. If the non-fuel-optimal landing aimpoint was the higher ranked alternative (#2) and was well within the outer contour, subjects were confident that they could still reach that landing aimpoint. This tradeoff between fuel cost and improved landing site appeared to favor the latter when the subject was provided detailed information about the fuel usage. Further investigation is needed on this aspect of the decision-making process. A display element was developed previously that provided the user with detailed information about the terrain parameters used by the ALHAT ranking algorithm (slope, roughness, distance from hazard) (Needham, 2008). This previous display element could be combined with the achievability contour element to investigate the landing point designation decision process when the subjects know not only the fuel cost information, but also the detailed rating information for each landing aimpoint.

Touchdown fuel was the only performance metric that demonstrated a significant effect of display. The achievability contour display resulted in lower fuel remaining at touchdown. This was the opposite effect than was expected, and likely relates to the reduced selection of the fuel optimal landing aimpoint. To directly measure the improved fuel information that the pilot receives from the achievability contour display, a separate experiment should be run that emphasizes maximizing touchdown fuel as the only performance goal.

5.3 Subjective Scales

The SART and Modified Bedford subjective rating scales were used in this experiment. The Despite one subject that had a difficult time assessing their own workload, the Modified Bedford ratings did show sensitivity to the experimental parameters, and would be recommended for use in a future experiment. The SART scale did not have an inherent anchoring mechanism provided by the flowchart used with the Modified Bedford scale. The SART scale also does not provide a clear, concise definition of the adjectives used for rating. To be effective, all subjects must agree on what is being rated. The data indicated large variations between subjects in SART ratings, which are indicative of a lack of similar anchoring. Based on the experimental results, future experiments should include a more reliable measure of situation awareness. Possible alternatives include freeze methods such as the Situation Awareness Global Assessment Technique (SAGAT, (Endsley, 1995)), or a verbal protocol such as that used in a recent thesis (Hainley, 2010).

5.4 Subject Experience

Experience of the subject showed an effect on several of the touchdown performance parameters (range, attitude, velocity) and attitude MSE. Those with considerable piloting experience performed better than those with simulator experience. It was expected that experience in the lunar landing simulator would be as helpful for flight and touchdown performance as piloting experience. This was not the case, and while the pilots performed better than all of the other subjects, there was no observable difference between the subjects with simulator experience and those with no experience in either simulators or piloting. Given the large performance difference and the likelihood of the recruitment of skilled pilots in future lunar landings, further experiments should focus on recruiting subjects with piloting experience.

5.5 Factors in Landing Point Selection

There were several additional elements that subjects reported in their decision-making process that were not measured explicitly. First, several subjects indicated that their selection process depended on the control mode used. In automatic control, they were more likely to select the fuel optimal landing aimpoint, even if a large attitude maneuver was required to reach the new target. This was reported to relate to a high level of trust in the automatic guidance to achieve any desired landing aimpoint. In manual mode, these same subjects reported a tendency to select landing aimpoints that required less extreme maneuvers (such as downrange of the currently designated target), due to a lack of trusting their own piloting abilities. Second, several subjects reported the desire to perform a redesignation early in the trials, prior to any required redesignation. This occurred in cases where the vehicle trajectory flew over an alternate landing aimpoint, and thus the subjects could stop short and quickly descend to the surface to save fuel. For the purposes of this experiment, subjects were only allowed to redesignate when required, but future experiments may investigate this pre-emptive redesignation behavior. Third, subjects reported the tendency to simply select the closest landing aimpoint when provided the auditory display. In theory, information in the displays including the range, horizontal velocity, altitude, and time to landing could be used in coordination with the auditory callouts to compute the fuel at landing. In practice, subjects skipped the mental computation, and selected the closest landing aimpoint. This represents a dangerous tendency for actual lunar landings, since the closest landing aimpoint to the vehicle is not always the most fuel efficient, which in actuality also depends on current vehicle horizontal velocity, attitude, and altitude, as well as elevation of the target.

5.6 Future Work

Additional implementations of the achievability contour display may increase the beneficial effects of the display and are worthy of investigation. Development of a heads-down perspective view display that includes the achievability contours would match recent developments in brown-out display technology (Sykora, 2009), and could also act to improve performance in the presence of dust simulations. To remove the change in orientation associated with switching from a forward to a birds-eye display, the achievability contours could be incorporated into a heads-up display (HUD). The ideal number and presentation of the contours themselves to maximize effectiveness should also be investigated in further detail.

The simulation environment used in the experiment can also be improved upon for future experiments. An out-the-window view was not included for this experiment, and should be implemented in simulation to more accurately portray the lunar landing information sources. This is particularly important given that as determined in the goal-directed task analysis, out-the-window visual information represents an important part of the landing point designation decision-making process. An analysis should be done investigating the ability of subjects to combine the out-the-window information with the achievability contours and pre-defined landing site recommendations to select a safe landing aimpoint. While the achievability contour algorithm was designed to be able to incorporate terrain elevation information, the terrain used in the experiment was fairly flat. Investigations should be performed on the effect of unusual terrain features (e.g. craters or cliffs) on the usefulness of the achievability contours. This area of research is particularly important given that future lunar landing systems are intended to have global reach, and highly cratered and rocky areas such as the lunar south pole are under strong consideration for manned landings.

Further research could also be performed by changing the vehicle models and parameters used in the simulation. As the next generation lunar lander design is refined, the models used in this experiment can be updated for accuracy. In the simulation used for the experiment in this thesis, there was no possibility for vehicle or display errors to occur. This resulted in a high trust in the automation used. The implications of this trust could be examined by introducing failures into the system, and examining the changes in subject behavior based on the presence or possibility of failures. This could include errors in the hazard detection system, where the presented hazard information in the display does not exactly match the out-the-window terrain. These hazard differences might result in changes in decision-making behavior, and merit investigation.

Due to recent political shifts, manned lunar landing may not be the focus of near-term space exploration. It is important to note that the achievability contour display concept is also applicable to any energy-constrained landing on a planetary body. Versions of the display could be developed and tested for landing simulations for Mars or other terrestrial or extra-terrestrial locations. Models developed would need to incorporate different gravitational parameters as well as atmospheric simulation (if applicable).

5.7 Summary

An achievability contour display was designed and implemented in a lunar landing simulation. An experiment was conducted testing the effects of the display on workload, situation awareness, performance, and decision-making under both automatic and manual control modes. The display showed improvements in subjective situation awareness and workload, indicating promising benefits during the landing point designation task. The display also had an effect on the decision-making during LPD, providing additional confidence for the user to select desired landing points within the contour area. Additional implementations of this display concept should be tested to maximize the benefits of the display.

Bibliography

(1969). *Apollo 11 Technical Crew Debriefing.* Houston, Texas.

(1969). *Apollo 12 Technical Crew Debriefing.* Houston, Texas: National Aeronautics and Space Administration.

(1971). *Apollo 15 Technical Crew Debriefing.* Houston, Texas.

Apollo Operations Handbook, Lunar Module, LM 10 and Subsequent, Volume I, Subsystems Data. (1971, April). *NAS 9-1100* .

Augustine, N. (2009). *Seeking a Human Spaceflight Program Worthy of a Great Nation.* Washington, D.C.: Review of Human Spaceflight Plans Committee.

Billimoria, K. (2008). Effects of Control Power and Guidance Cues on Lunar Lander Handling Qualities. *AIAA Space 2008 Conference* .

Brady, T., & Paschall, S. (2010). The Challenge of Safe Lunar Landing. *Proceedings of the IEEE Aerospace Conference* .

Brown, C. (1999). *Human Computer Interface Design Guidelines.* Great Britain: Intellect Books.

Cheatham, D., & Bennett, F. (1966). Apollo Lunar Module Landing Strategy. *Apollo Lunar Landing Symposium* .

Chua, Z., Major, L. M., & Feigh, K. (2009). Modeling Cockpit Interface Usage During Lunar Landing Redesignation. *International Symposium on Aviation Psychology.*

Clark, T. (2010). Human Spatial Orientation Perceptions During Simulated Lunar Landing. *Thesis M.S.* Massachusetts Institute of Technology.

Cohanim, B. C. (2009). Landing Point Designation Algorithm for Lunar Landing. *Journal of Spacecraft and Rockets* .

Cohen, M. M. (2009). From Apollo LM to Altair: Design, Environments, Infrastructure, Missions, and Operations. *Proceedings of the AIAA Space Conference* .

Cummings, M., & Wang, E. a. (2005). *Conceptual Human Interface Design for a Lunar Access Vehicle.* Cambridge, MA: MIT Humans and Automation Laboratory.

Dollfus, A., Bowell, E., & Titulaer, C. (1971). Polarimetric Properties of the Lunar Surface and its Interpretation. Part II. Terrestrial Samples in Orange Light. *Astronomy and Astrophysics* , 10:450.

Duda, K., Johnson, M., & Fill, T. (2009). Design and Analysis of Lunar Lander Manual Control Modes. *IEEE Aerospace Conference*, (pp. 1-16). Big Sky, MT.

Endsley, M. (1995). Measurement of Situation Awareness in Dynamic Systems. *Human Factors* , 65-84.

Endsley, M. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors* , 32-64.

Endsley, M., Bolte, B., & Jones, D. (2003). *Designing for Situation Awareness: An approach to user-centered design.* New York: Taylor & Francis.

Epp, C. R. (2008). Autonomous Landing and Hazard Avoidance Technology. *IEEE Aerospace Conference* .

Epp, C., & Smith, T. (2007). The Autonomous Landing and Hazard Detection and Avoidance Technology. *IEEE Aerospace Conference* .

Farkas, A. J. (1972, March). Apollo Experience Roport - Lunar Module Display and Control Subsystem. *NASA Technical Note D-6722* . Houston, TX: National Aeronautics and Space Administration.

Forest, L., Cohanim, B., & Brady, T. (2008). Human Interactive Landing Point Redesignation for Lunar Landing. *Proceedings of the IEEE Aerospace Conference* .

Hainley, C. (2010, October). Lunar Landing: Dynamic Operator Interaction with Multi-Modal Automation Systems. *Masters Thesis* . Massachusetts Institute of Technology.

Helander, M., Landaurer, T., & Prabhu, P. (1997). *Handbook of Human-Computer Interaction.* Elsevier.

Johnson, A. (2010). An Integrated Traverse Planner and Analysis Tool for Future Lunar Surface Exploration. *Masters Thesis* . Massachusetts Institute of Technology.

(1971). *LM 11 Operations Handbook Volume II: Operational Procedures.* NAS 9-1100: NASA Spacecraft Systems Branch / Flight Crew Support Division.

Lunar Module Systems Handbook: LM-5 to LM-9. (17 January 1969). NASA Document FC027.

Major, L., Cohanim, B., & Brady, T. (2008). Human Interactive Landing Point Redesignation for Lunar Landing. *IEEE Aerospace Conference.* Big Sky, MT.

McCandless, J. e. (2005). Evaluation of the Space Shuttle Cockpit Avionics Upgrade (CAU) Displays. *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Orlando, FL.

McCluskey, R., Clark, J., & Stepaniak, P. (2001). Correlation of Space Shuttle Landing Performance with Cardiovascular and Neurovestibular Dysfunction Resulting from Space Flight.

Merfeld, D. (2003). Rotation Otolith Tilt-Translation Reinterpretation (ROTTR) hypothesis: A New Hypothesis to Explain Neurovestibular Spaceflight Adaptation. *Journal of Vestibular Research* , 309-320.

Mindell, D. A. (2008). *Digital Apollo.* MIT Press.

Mindell, D. (n.d.). *Digital Apollo Cover.* Retrieved from Digital Apollo website: http://web.mit.edu/digitalapollo/DigitalApolloCover.jpg

Needham. (2008, September). Human-Automation Interaction for Lunar Landing Aimpoint Redesignation. Masters Thesis: Massachusetts Institute of Technology.

Oravetz, C. (2009). Human estimation of slope, distance, and height of terrain in simulated lunar conditions. *Thesis M.S.* Massachusetts Institute of Technology.

Paschall, S. B. (2009). A Self Contained Method of Safe and Precise Lunar Landing. *IEEE/AIAA Aerospace Conference* , March 7-14, Big Sky, MT.

Roscoe, A., & Ellis, G. (1990). *A Subjective Rating Scale Assessing Pilot Workload in Flight: A Decade of Practical Use.* Farnborough, UK: Royal Aerospace Establishment Technical Report 90019.

Sostaric, R. (2007). Powered Descent Trajecotry Guidance and Some Considerations for Human Lunar Landing. *30th Annual AAS Guidance and Control Conference* .

Sykora, B. (2009). Rotocraft Visual Situation Awareness: Solving the Pilotage Problem for Landing in Degraded Visual Environments. *American Helicopter Society 65th Annual Forum.* Grapevine, TX.

Taylor, R. (1990). *Situation Awareness Rating Technique (SART): The Development of a Tool for Aircrew Systems Design.* AGARD, Situational Awareness in Aerospace Operations.

Tsang, P., & Vidulich, M. (2003). *Principles and Practice of Aviation Psychology.* New Jersey: Lawrence Erlbaum Associates.

Young, L., Oman, C., Watt, K., & Lichtenberg, B. (1984). Spatial Orientation In Weightlessness and Readaptation to Earth's Gravity. *Science* , 225:205-208.

Appendix I – Perceptual Difficulties and Spatial Disorientation in Spaceflight

Lighting

Lunar regolith exhibits non-Lambertian reflectance properties (Dollfus, Bowell, & Titulaer, 1971) that could degrade human visual performance during a lunar landing. Briefly, light reflects off the regolith directly back in the direction from which it contacted the surface; there is no scattering of light. This restricts the set of reasonable landings based on the position of the sun: if the landing is down-sun, bright reflections back at the spacecraft from the lunar surface could wash out details of the local hazards in the landing area. This property also results in a general increase in the lighting contrast of objects on the surface. That is, bright objects appear brighter and shadows appear very dark. Research has shown that these properties degrade the ability of a human to discern slopes and distances on the lunar surface (Oravetz, 2009).

The lighting issues caused by the unusual regolith properties are further compounded by shallow sun angles in locales near the lunar poles. The lunar poles (particularly the lunar south pole) have been identified as scientific areas of interest, typically related to craters that experience perpetual darkness (Brady & Paschall, 2010). At the poles, sun angles typically range between X and X degrees, which result in long shadows along the lunar surface. These shadows can limit the amount of the surface visible to astronauts during landing, which may hinder the ability to identify hazards and select safe landing aimpoints.

Dust

As the lander descends to the lunar surface, the descent engine disturbs the thin layer of superficial lunar dust. The dust spreads outwards radially from the spacecraft, and can obscure the astronauts' view of local hazards (e.g. boulders, craters), or the view of the horizon. All Apollo missions reported seeing lunar dust during the terminal descent, with some reporting dust appearing as high as 200ft altitude (Apollo 12 Technical Crew Debriefing, 1969). The loss of visual information can result in inadequate identification of local hazards, as has been seen from the Apollo missions and reports (Brady & Paschall, 2010). Pete Conrad, the commander of Apollo 12, recognized that the dust reduced his ability to perceive the hazards in the landing area with the following quote:

> *"…we picked up a tremendous amount of dust much more so than I expected. I could see the boulders through the dust, but the dust went as far as I could see in any direction and completely obliterated craters and anything else. All I knew was there was ground underneath that dust. I had no problems with the dust determining horizontal and lateral velocities, but I couldn't tell what was underneath me."* – Charles "Pete" Conrad (Apollo 12 Technical Crew Debriefing, 1969)

In addition to hazard identification issues, obscuration of the horizon could result in misinterpretation of the subjective orientation, which could lead to inappropriate control inputs (Clark, 2010). The flow of material outwards from the vehicle during the descent could also result in a sensation of vection in the opposite direction, possibly resulting in spatial disorientation.

Spatial Disorientation

Spatial disorientation is a condition in which the human perception of direction (through visual, vestibular, and proprioceptive inputs) does not agree with reality (Clark, 2010). The Apollo landings provide the only source of manned lunar landing to examine for possibilities of spatial disorientation. It should be noted that none of the Apollo astronauts reported any kind of disorientation during the landing process. However, comments from the debriefings and landing performance during the Apollo missions may indicate some anecdotal evidence for spatial disorientation. In Apollo 11, Niel Armstrong recognized the degradation of his ability to perceive the motion of the spacecraft as it came down to the lunar surface, as described in the following quote:

> *"The exhaust dust was kicked up by the engine and this caused some concern in that it degraded our ability to determine not only our altitude and altitude-grade in the final phases, but also, and probably more importantly, our translational velocities over the ground."* – Neil Armstrong (Apollo 11 Technical Crew Debriefing, 1969)

Landing performances in the Apollo landings have also indicated some lack of awareness in position relative to local hazards in the landing area. In fact, upon analyzing images from Apollo, one can identify potentially dangerous local hazards near the lander in all six of the landings (Brady & Paschall, 2010). In Apollo 15, the landing set two of the vehicle legs in a crater, resulting in damage to the descent engine bell (Apollo 15 Technical Crew Debriefing, 1971). Vehicle design also plays a role in spatial disorientation, with the position of the astronauts relative to the vehicle center of gravity affecting the inputs to the vestibular system (Clark, 2010). Some designs for future landers have positioned fuel tanks such that the view out the window becomes more restrictive (Cohen, 2009). These types of vehicle parameters must be considered in the design of systems to support astronaut tasks such as LPD.

The NASA Space Shuttle program provides additional evidence for spatial disorientation in spaceflight. The reappearance of the planetary gravitational field after adaptation to microgravity during entry and landing can impact astronauts' perceptions and create illusions. Astronauts have reported vertigo, oscillopsia, and reduced visual acuity during shuttle landings typically coinciding with movements of the head. Illusions occurring with head tilt have also been reported (Young, Oman, Watt, & Lichtenberg, 1984) (Merfeld, 2003). Post-landing neurovestibular symptoms have been shown to correlate with poorer landing performance based on touchdown speed and descent rate at touchdown (McCluskey, Clark, & Stepaniak, 2001).

Spatial disorientation in aviation occurs irregularly; a pilot might only experience spatial disorientation a few times in a thousand or more hours of flight time. Different pilots might also show differing susceptibility to spatial disorientation for any particular set of stimuli. In the height of the Apollo program, astronauts may have been reticent to admit spatial disorientation even if they recognized its occurrence, under concerns that it might compromise their selection for future missions. Given that only twelve astronauts experienced the lunar landing stimuli and the anecdotal evidence provided, we cannot ignore the possibility of spatial disorientation during a future manned mission to the lunar surface.

Geographic Disorientation

Geographic disorientation occurs when the perception of position differs from reality on a large scale, such as relative to major landmarks. In Apollo, landmark navigation was an important part of the descent, to orient the astronauts after the lunar surface had come into view. During training astronauts were taught to recognize certain formations of craters or other large surface features to ensure the vehicle was on the appropriate trajectory. While most of the Apollo astronauts reported quick recognition of the navigational landmarks, Apollo 15 included an instance of geographic disorientation as commander Dave Scott did not recognize the view of the lunar surface (Mindell D. A., 2008), as indicated in the quote from the debriefing below:

> *"(The second event was that) I looked out the window, and I could see (Mt.) Hadley Delta. We seemed to be floating across Hadley Delta and my impression at the time was that we were way long because I could see the mountain out the window and we were still probably 10,000 to 11,000 feet high. I couldn't see the rille out the forward corner of the window, which you could on the simulator, out the left forward corner. So, I had the feeling from the two calls that we were going to land long and south."* (Apollo 15 Technical Crew Debriefing, 1971)

Maintaining geographic awareness will be crucial for future missions, as good orientation is required for quick recognition of the location of the landing target position relative to the vehicle. Incorrect determinations of current position could lead to dangerous control errors in accordance with the perceived location rather than the actual location.

Appendix II – Notes from Usability Testing (combined across several subjects)

Comments/Recommendations on PFD

- Add numeric value to velocity vector
- Add numeric values to hdot scale
- Possible use of separate lateral and forward velocity components
- Color coding on descent rate
- Need an indicator in real-time that displays how much fuel you will land with – provide info as to how you're doing along the way with respect to fuel. (Potentially a fuel flow indicator plus a fuel remaining predictor)
- Lateral velocity indicator should be heading up. Consider changing the scale when near hover to have increased sensitivity to trim residuals. Green vector color is okay. Re-scaling should be automatic and would be something the crew would get used to (provide indicator to the pilot of the new scale).
- Suggest re-scaling the fuel thermometer after pitch-over to be more sensitive during the approach and terminal descent.
- Didn't see a need to show pitch and roll rates. You get a feel for that by how fast the guidance needles move.
- Backlighting or highlighting of the flight mode when there are changes.
- Color code the equipment limitations (e.g., max descent rate), also show the recommended/desired vertical speed.
- Text/font size should be a little bigger.
- Wanted larger text on most of the display – felt that there was plenty of space, so some of the elements could be made larger to accommodate larger/bolder text
- Enlarge contact light and change to yellow to make it stand out
- Mode indicator for velocity vector (to make it obvious if it was high or low scale)
- Wanted high contrast fills (black?) for many of the shapes on the display – felt that the blue/ brown background moving behind the scales made it harder to read and interpret
    - Fuel
    - Altitude tape
    - Vertical Velocity
    - Time to go
    - Mode
- Was very adamant about wanting the XDOT, YDOT, and XBAR numeric readouts to be in simpler terms (FORE/AFT, LEFT/RIGHT, UP/DOWN)
- Felt that attitude rates were not needed for this display, even though they were available in Apollo
- Wanted a slightly larger point on the ownship symbol to overlap with the guidance crosshairs
- Move the heading guidance to the outside of the compass rose, and make it a filled-in shape
- Provide numeric scale on horizontal velocity demarcations (shown as .. in the display)

Comments/Recommendations on Contour Display

- Possibly located in between Commander and LMP, also potentially on HUD

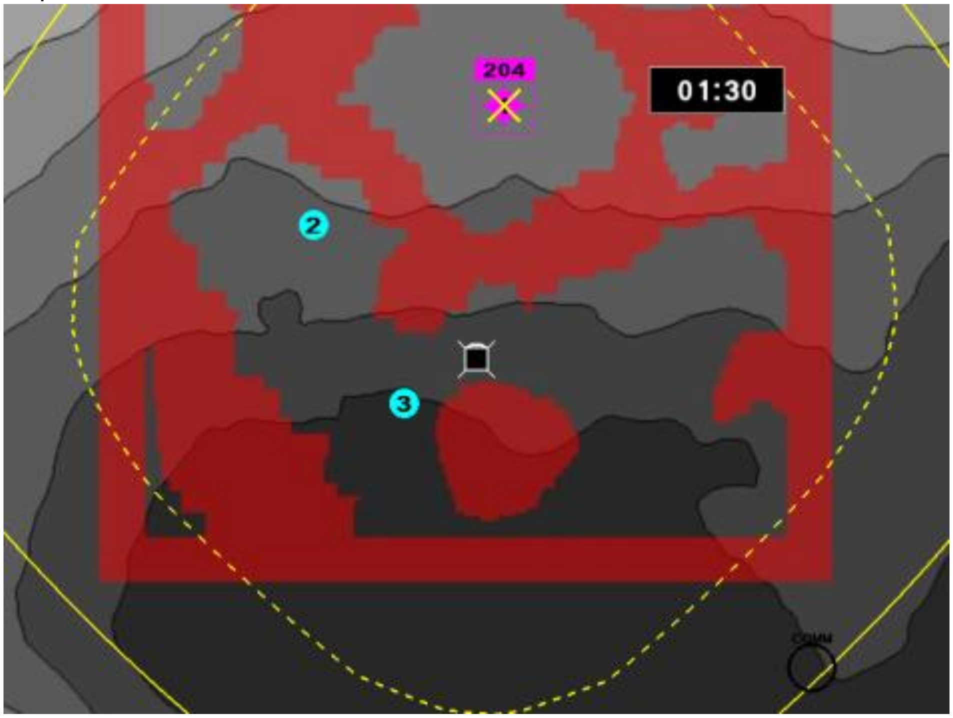
- Include slant range to target
- Make display zoomable to see fine resolution of movement with respect to LP
- Likely a secondary display because it isn't changing as rapidly.
- Add symbology in addition to the currently designated landing target to disambiguate from the others. Suggest box and/or cross hairs.
- Having hazard highlighting outside the ALHAT defined box would make for a messy display. Since there is no new information outside the ALHAT box, marking the area is erroneous.
- Provide a zoomed in view of the area surrounding the targeted LAP when at a hover point above it.
- Thought a 3-D map / wingman-type display would be a good thing to have and would be something that could naturally train.
- Wants a scale for the map, though he indicated that the box around the landing site being a certain known size was sufficient for scaling purposes
- Felt that it should be left as a 2D display the way it is (as compared to HUD or 3D display), though there may be trouble in integration of out-the-window view with heads down display
- Wanted hazards to be marked with different colors depending on whether it represents a hazard above (boulder) or below (crater) the surface horizontal
- Strongly felt that the achievability information should be shown to/used by the commander, rather than the LMP

Appendix III – Experimental Maps

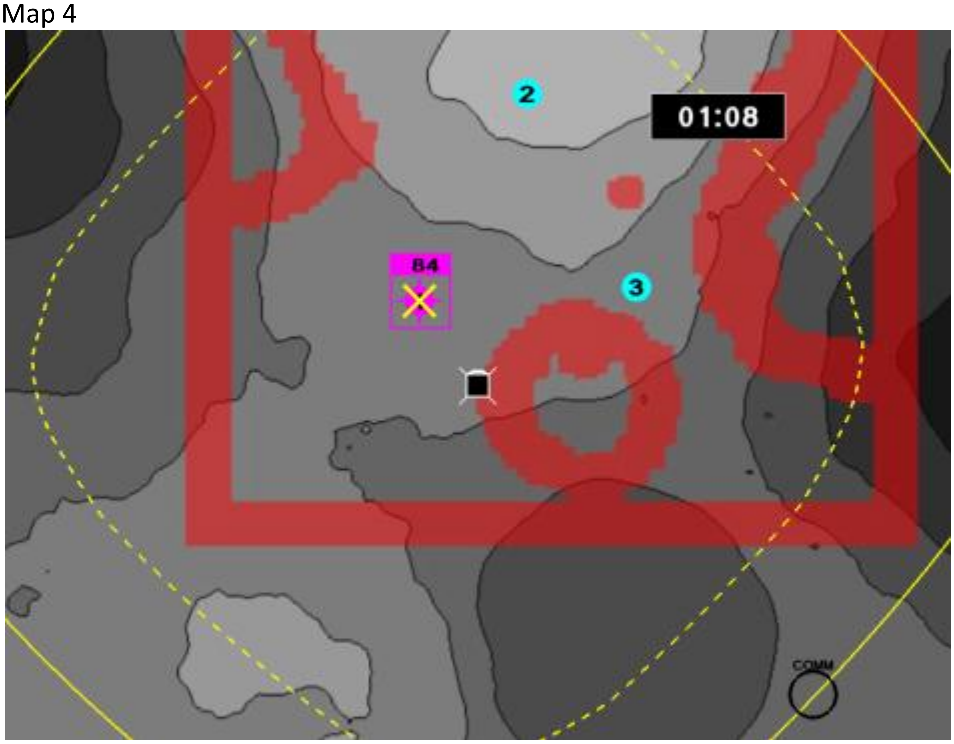
Map 1

Map 2

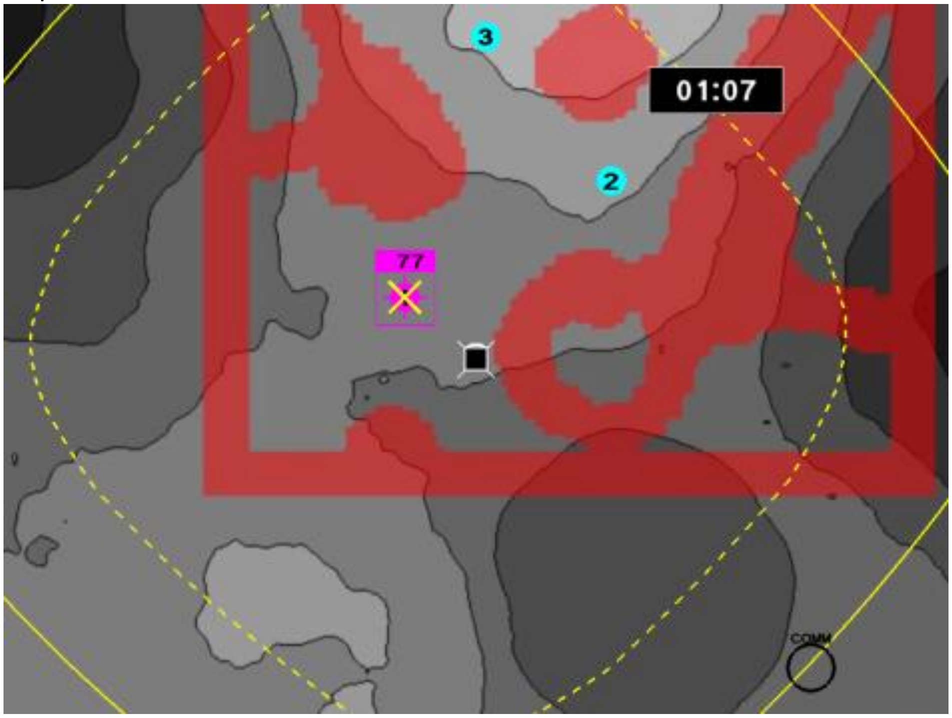
Map 3



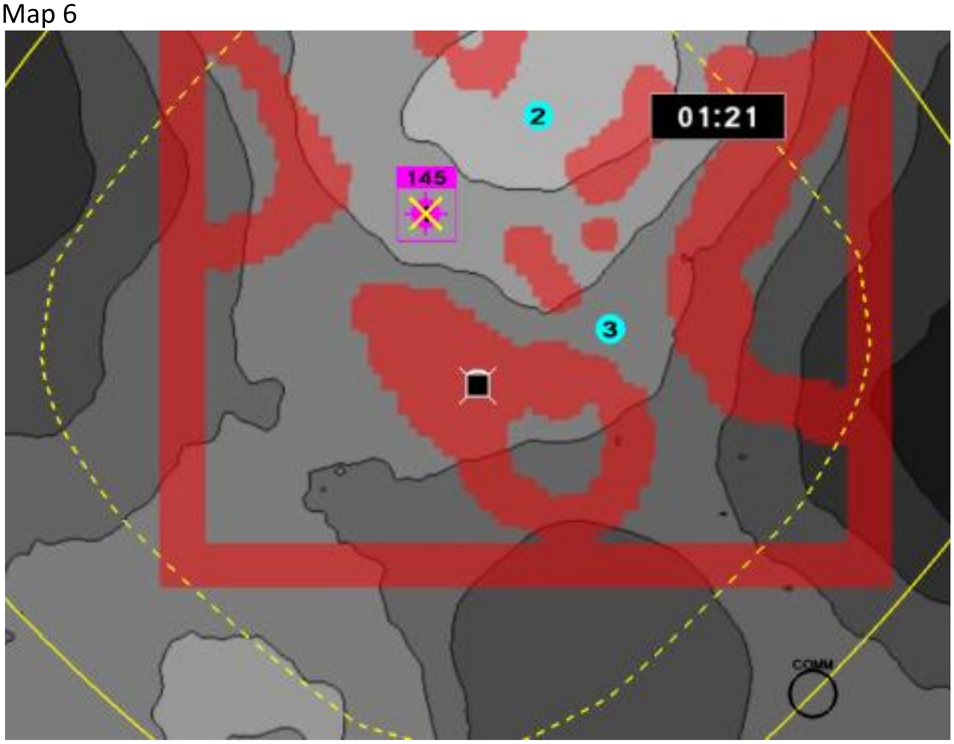
Map 4



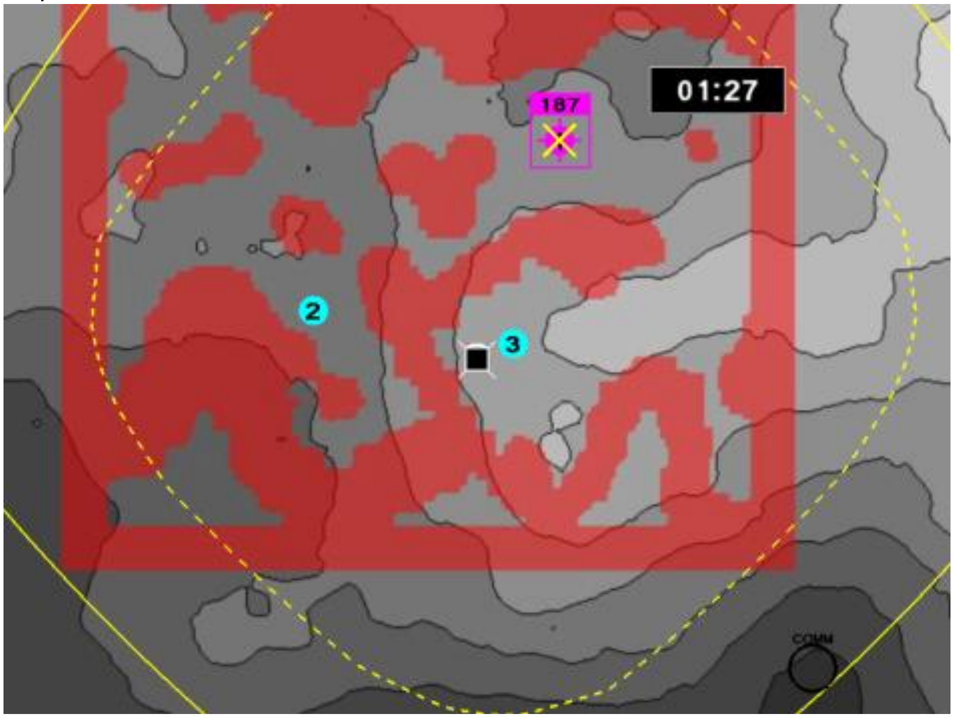
Map 5



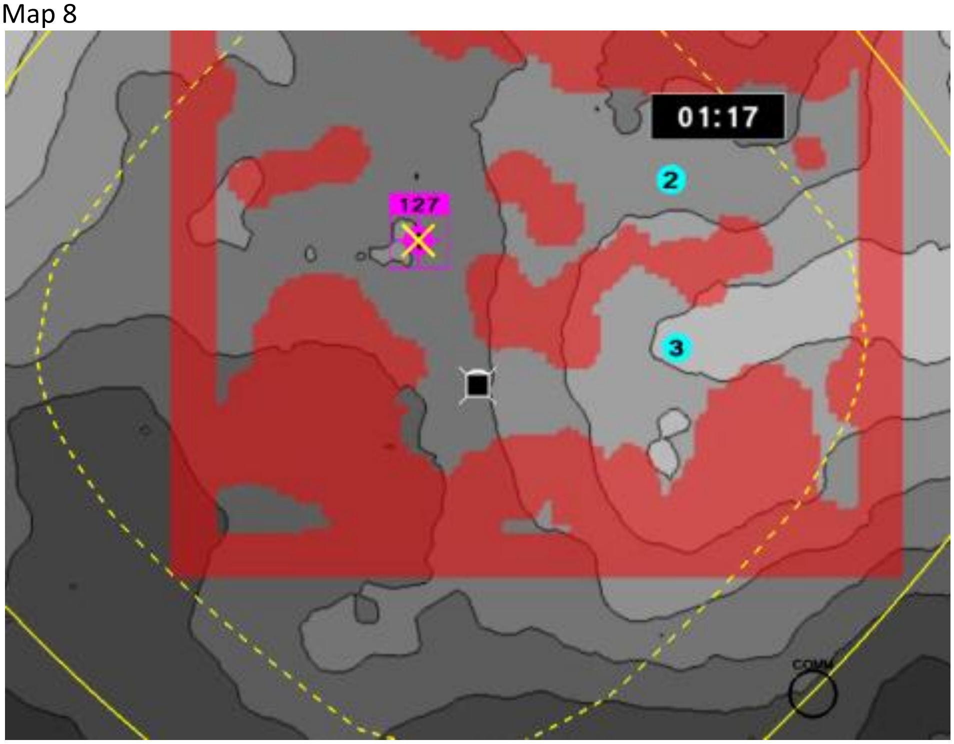
Map 6



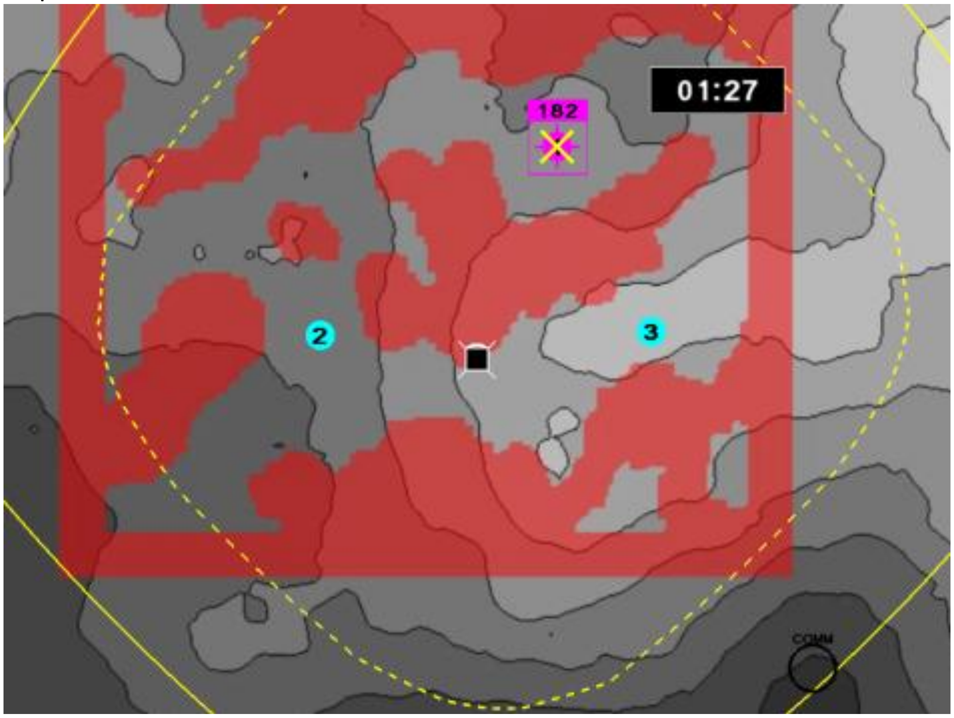
Map 7



Map 8



Map 9



Appendix IV – Secant Method

Secant method is a root finding method that uses a succession of roots of secant lines from the function to narrow in on the actual root. The general formulation of the secant method is as follows:

$$x_n = x_{n-1} - f(x_{n-1})\frac{x_{n-1} - x_{n-2}}{f(x_{n-1}) - f(x_{n-2})}$$

The secant method has the advantage of not requiring the root to be bounded as the bisection method does, but does not converge as quickly as Newton's method. There are also cases where the secant method does not converge if the target function is not well-behaved (such as a step function around the root).

In this case, secant method was selected to find the intersection with the terrain regardless of needing to bound the root, and in the absence of knowing the derivative of the target function (as would be required by Newton's method).

Appendix V – Demographic Survey

Gender: F M **Age**: _____

Writing Hand: Right Left **Major/Course # (if applicable)**: __________

Colorblind? Y N (If yes, can you differentiate between red and green? ________________________)

1. **Do you have experience with Virtual environments (e.g. 3-D games, CAD, graphic design, etc.)?**
(Yes No) (If "Yes," can you please describe this experience?)

2. **Do you have experience with joysticks/game controllers? (e.g. computer/video games, robotics)**
(Yes No) (If "Yes," can you please describe this experience?)

3. **Do you have experience with computer based flight simulators?**
(Yes No) (If "Yes," can you please describe this experience?)

4. **Do you have any flight experience? (e.g. recreational aircraft, military aircraft, pilot's licence)**
(Yes No) (If "Yes," can you please describe this experience?, if "No", go to question 6)

5. **About how many flight hours have you logged <u>in the past 3 years</u>?**
☐ <10 ☐ 10-25 ☐ 25-50 ☐ 50-100 ☐ > 100

6. **How many hours per day do you use the computer?**
☐ 0 ☐ 1 – 3 ☐ 3 – 5 ☐ 5 – 7 ☐
More than 7

7. **Have you previously or do you currently play video/computer games?**
(Yes No) (If "No", skip questions 8 and 9)

8. **On average, how often (hours/week) have you played video/computer games <u>in the past 3 years</u>?**
☐ 0 ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

9. **What kind of video/computer games do you play the most? (check as many as apply)**
☐ First person ☐ Role-playing/Strategy ☐ Arcade/Fighting

☐ Simulation (driving, flying) ☐ Sports ☐ Other ______________

Thank you. Please give this questionnaire back to the experimenter.

Appendix VI – Experimental Matrix

Randomly generated:

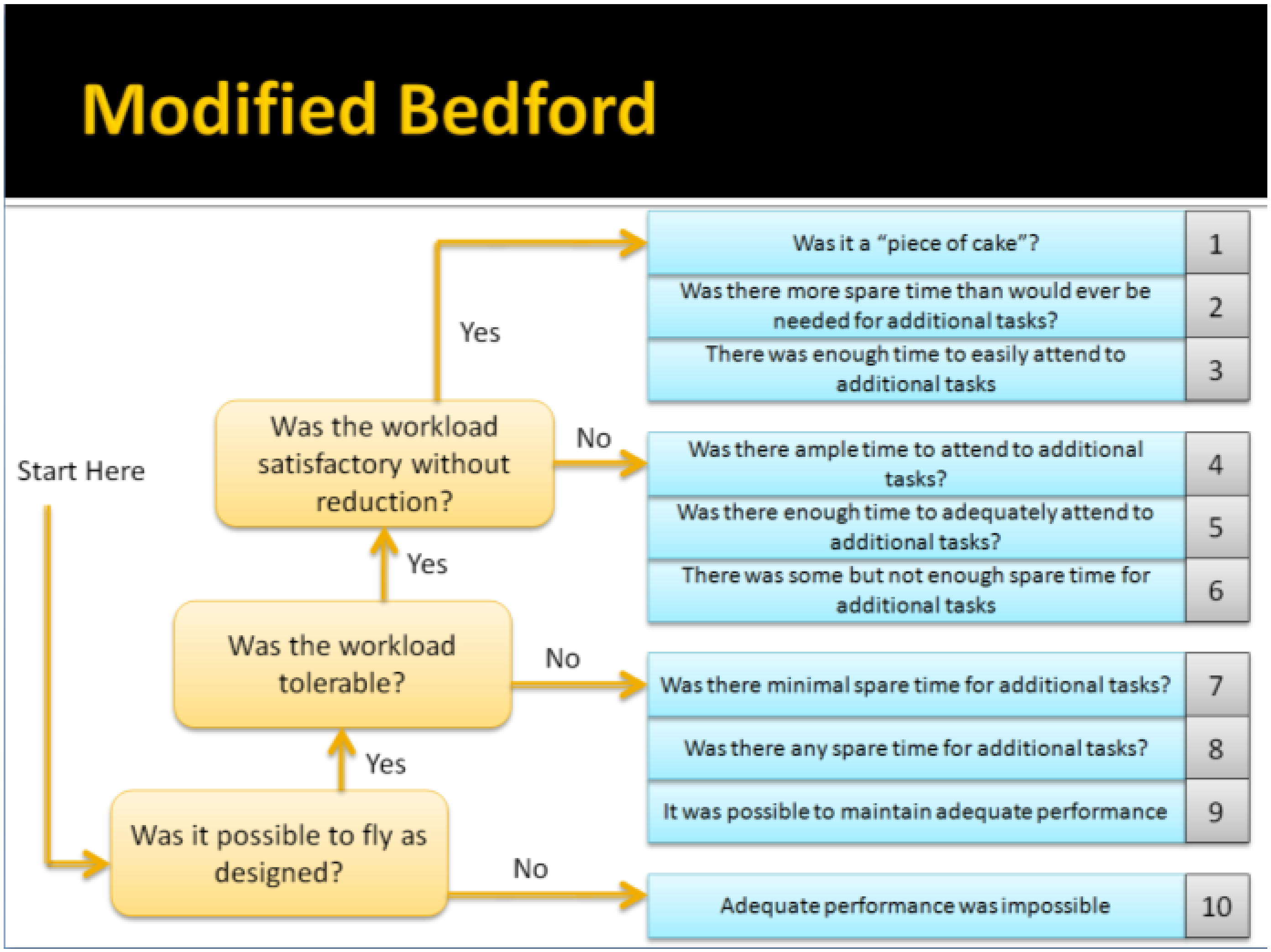
Control Type S = Manual Control
Control Type M = Supervisory Control
Display Type 0 = Auditory
Display Type 1 = Contour
Map 1a = map 1
Map 1b = map 2
Map 1c = map 3
Map 2a = map 4
Map 2b = map 5
Map 2c = map 6
Map 3a = map 7
Map 3b = map 8
Map 3c = map 9
* Indicates Early Redesignation
** Indicates Late Redesignation

Order in experimental matrix is across columns (left to right). Therefore, the first trial is condition S01a*, and the last trial is S03b

Initial "Throwaway" Trials:
S13c
S01c*
M11b**
M02c**

S01a*	S13a**	S02a	S11b	M12b**	M03b	M13c	M01c*
S12c	S03a	S11b**	S03b*	M02b	M11a*	M01b**	M12c
M03c	M12a*	M13a	M02b**	S01c	S13b	S02c**	S11a*
M12a**	M01c	M02a*	M11a	S13c*	S03a**	S12b	S03b

Appendix VII – Modified Bedford Flowchart



Appendix VIII – SART Rating Sheet

SART Descriptions

Rate these three

Category	Subcategory	Definition
Demand on Attentional Resources	Instability	Likeliness of situation to change suddenly
	Complexity	degree of complication of situation
	Variability	number of variables which require one's attention
Supply of Attentional Resources	Arousal	degree to which one is ready for activity (sensory excitability)
	Concentration	degree to which one's thoughts are brought to bear on the situation
	Division of Attention	degree of distribution or focusing of one's perceptive abilities
	Spare Capacity	amount of mental ability available to apply to new variables
Understanding of the Situation	Information Quantity	amount of knowledge received and understood
	Information Quality	degree of goodness or value of knowledge communicated
	Familiarity of the Situation	degree of acquaintance with situation, experience

Appendix IX – Subject Recruitment Form

MIT Human Subjects Needed for

Lunar Landing Sensorimotor Experiments

Man Vehicle Laboratory

Department of Aeronautics and Astronautics

National Space Biomedical Research Institute

Massachusetts Institute of Technology

We are running a series of experiments investigating the potential sensorimotor issues connected with lunar landings and evaluating candidate displays that address these issues. Subjects will be trained and tested in simulated lunar landings. For some experiments, subjects must have actual flight or flight-simulator experience and demonstrable knowledge of moving-map situation awareness displays. One or two training and testing sessions are needed, each 1-2 hours in length. $10/hr.

For further information contact: Liz Zotos, Room 37-219, 617 253-7805

Appendix X – COUHES Approval Forms

CONSENT TO PARTICIPATE IN

NON-BIOMEDICAL RESEARCH

Sensorimotor interaction with vehicle displays and controls to enhance human-machine interaction cooperation during precision lunar landing: Evaluation of Enhanced Displays Supporting Precision Lunar Landing

You are asked to participate in a research study conducted by Prof. Laurence Young, Ph.D., from the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (M.I.T.) and Kevin Duda, Ph.D., from the Charles Stark Draper Laboratory. You were selected as a possible participant in this study because NASA and the National Space Biomedical Research Institute are interested in understanding how to best design the human-machine interface used to control the lunar lander for future lunar missions. 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 goal of these experiments is to evaluate the efficacy of enhanced terrain and situation awareness displays in supporting an astronaut as they transition between supervisory and manual vehicle control modes during the approach for lunar landing. The proposed experiments will measure the subject's situation awareness, workload, and ability to select a safe landing point by combining a simulated out-the-window view and synthetic terrain view during a simulated landing. The results will help determine the recommended vehicle situation awareness displays for lunar landing.

- **PROCEDURES**

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

You will help evaluate the displays using a within-subjects design comparing 2-D plan view and auditory situation awareness displays. Three control modes will be used: 1) Supervisory, 2) 1-axis Manual, and 3) 2-axis Manual control. You will be instructed on the task of monitoring the lunar lander vehicle trajectory and performance during an autoflight and manual approach and descent. This includes some practice time to become familiar with the displays and controls of the simulator. After this, you will begin the experiment. The trials will begin with the lander at a fixed position above the lunar surface with approximately 1.5 minutes of fuel. In each trial the *a priori* targeted landing aimpoint may not be suitable, therefore potentially requiring you to make at least one LP re-designation by interacting with the simulator through one of the hand controllers. You may make more than one re-designation, if you decide that their initial selection is also unsatisfactory. You may be asked to complete up to eight repetitions for each display type and control mode combination, for a total of up to 48 trials. At the end of each trial, you may be asked to rate your situation awareness using a subjective situation awareness technique. At some point in each trial the scenario may be paused, and the experimenter will ask you several questions related to the state of the current trial. Upon completing the assessment, the scenario will resume and you will resume monitoring the simulated trajectory to touchdown. You may also be asked to complete the NASA TLX subjective assessment of workload after every three trials. You may also be asked to wear a heart rate monitor for the duration of the experiment. You will complete a total of up to 48 trials, each testing a different combination of cockpit displays, control modes, and landing conditions.

You will participate in a single experimental session which is expected to last approximately two to three hours, and will be offered a 5-minute break halfway through the trials. The entire session will take place in the Draper Laboratory's Lunar Lander Simulator.

- **POTENTIAL RISKS AND DISCOMFORTS**

    - Boredom due to the large number of repetitive trials.
    - Fatigue from operating the joysticks and attending to the displays and tasks
    - Symptoms of simulator sickness due to visual motion in the displays.
    - Minor skin irritation or discomfort from the heart rate monitor

You will be given short breaks between trials to reduce the risks of boredom, fatigue and motion sickness. You may request a break at any time during the experiment if you begin to feel any discomfort.

- **POTENTIAL BENEFITS**

There are no benefits to you aside from becoming familiar with the potential sensorimotor issues during lunar landing.

NASA will benefit from the results of these experiments by being able to design appropriate human-machine interfaces that will mitigate any risks from the sensorimotor issues studied.

- **PAYMENT FOR PARTICIPATION**

You will receive $10 per hour for your participation. Payment is prorated on the basis of time spent if you decide to withdraw**.**

- **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.

No personal information will be collected in this experiment. All performance data collected in this experiment will be coded to prevent the identification of data with a specific person. All data reported in journal or conference papers will be group data or de-identified. Data will be destroyed one year after all papers from this project are completed: this is estimated to be in 2012.

- **IDENTIFICATION OF INVESTIGATORS**

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

Principal Investigator: Prof. Laurence Young, 617-253-7759

Co-Investigator: Kevin Duda, 617-258-4385

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

If you feel you have suffered an injury, which may include emotional trauma, as a result of participating in this study, please contact the person in charge of the study as soon as possible.

In the event you suffer such an injury, M.I.T. may provide itself, or arrange for the provision of, emergency transport or medical treatment, including emergency treatment and follow-up care, as needed, or reimbursement for such medical services. M.I.T. does not provide any other form of compensation for injury. In any case, neither the offer to provide medical assistance, nor the actual provision of medical services shall be considered an admission of fault or acceptance of liability. Questions regarding this policy may be directed to MIT's Insurance Office, (617) 253-2823. Your insurance carrier may be billed for the cost of emergency transport or medical treatment, if such services are determined not to be directly related to your participation in this study.

- **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 E25-143B, 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

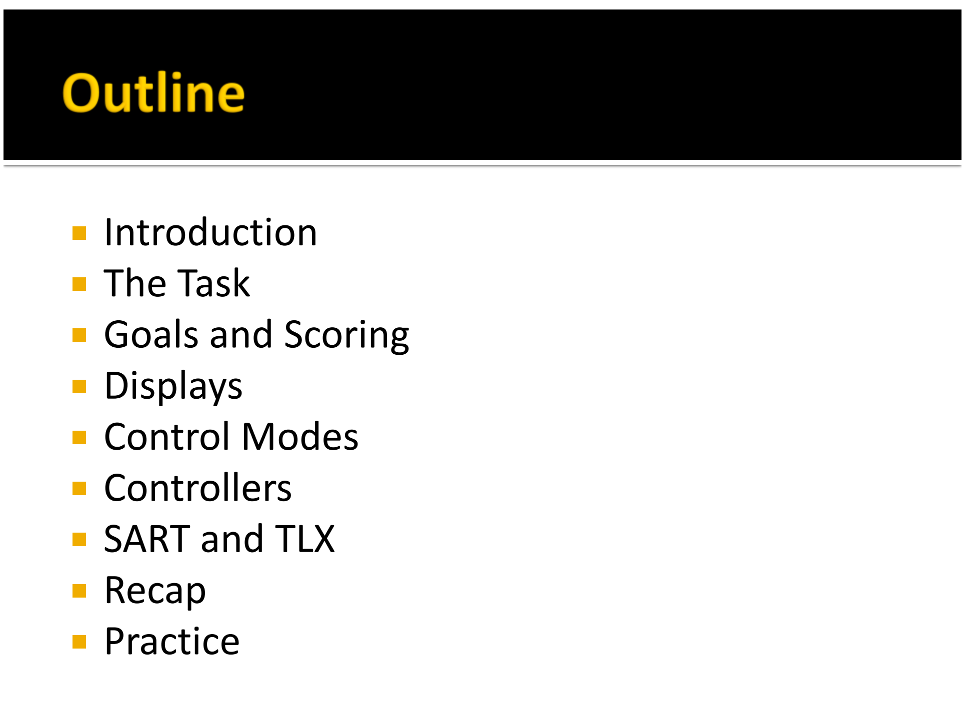
SIGNATURE OF INVESTIGATOR

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 XI – Training Slides

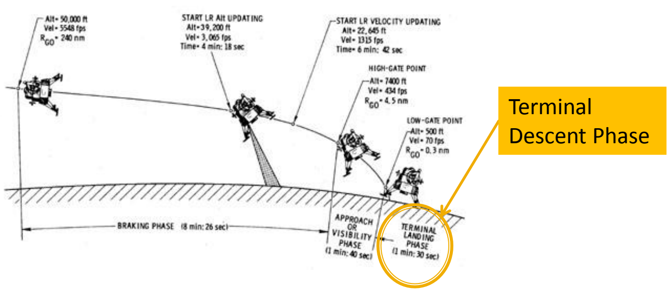


Introduction

- Landing humans safely on the moon requires the use of unusual vehicles and trajectories
- The astronaut has a challenging task of integrating information from multiple displays and using that information to command the vehicle to the surface

Introduction

- A typical lunar landing trajectory has 3 phases
  - Braking phase (deceleration out of orbit)
  - Approach phase (to establish visual contact with the surface)
  - Terminal descent phase (pilot directs the vehicle down to the surface)
- This experiment focuses on the terminal descent phase of landing



Introduction

- During the terminal descent, the astronaut has to confirm the final selection of a landing location, referred to as the landing aimpoint
- In Apollo, landing aimpoints were typically visually confirmed, and were often changed to different locations by the commander
- For future missions, several landing aimpoints will be recommended to the astronaouts by the ALHAT (Autonomous Landing and Hazard Avoidance Technology) system
- The astronaut must use his/her own judgment to select the final landing aimpoint

The Task

- It is your responsibility to guide a lunar lander down to the surface in a simulated terminal descent
- Several displays will be available to assist you, and you will make use of several control modes
- Guidance algorithms will also assist your landing efforts
- There will be a total of 36 landing simulations (about 2 minutes each)
- You will be using either supervisory (automated vehicle motion) or manual control (using a controller) to direct the vehicle

Goals

- Your primary goals are:
  - Select an appropriate landing aimpoint from among those recommended by ALHAT
  - Follow the flight director needles as closely as possible to ensure an accurate and safe landing
  - Achieve a good landing score at touchdown, based on
    - Small range from target (i.e. landing close to the aimpoint)
    - High remaining fuel margin
    - Low horizontal velocity
    - Small attitudes at landing (pitch and roll)
    - High distance to the nearest hazards
  - Minimize response time to communication signals

Scoring at Touchdown

- At the end of each landing, you will be given a score on various parameters, and provided one of 3 rankings for each category ("good", "adequate", or "poor")
- The rankings and requirements for each category are shown below

	Good	Adequate	Poor
Range	<16ft	<32ft	>32ft
Fuel	>2%	>1%	<1%
Horizontal Velocity	<4fps	<8fps	>8fps
Roll*	<6 degrees	<10 degrees	>10 degrees
Pitch*	<6 degrees	<10 degrees	>10 degrees

*All landing parameters are compared to "horizontal" orientation

Scoring at Touchdown

- An example touchdown scoring screen is shown below – you will have this shown to you at the end of each landing

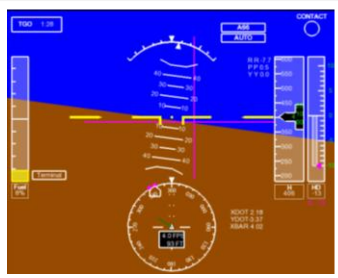
Landing Performance

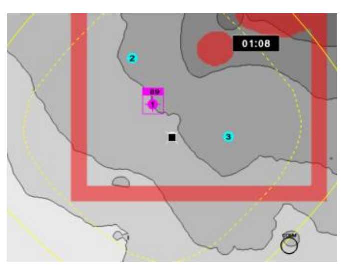
	Actual	Desired	Rating
Range	26.2 ft	<16ft	Adequate
Fuel	401.4 kg	>300kg	Good
Horiz Vel	2.2 ft/s	<4fps	Good
Roll	0.9 deg	+/-6deg	Good
Pitch	1.8 deg	+/-6deg	Good

- Try to get all "good" ratings!

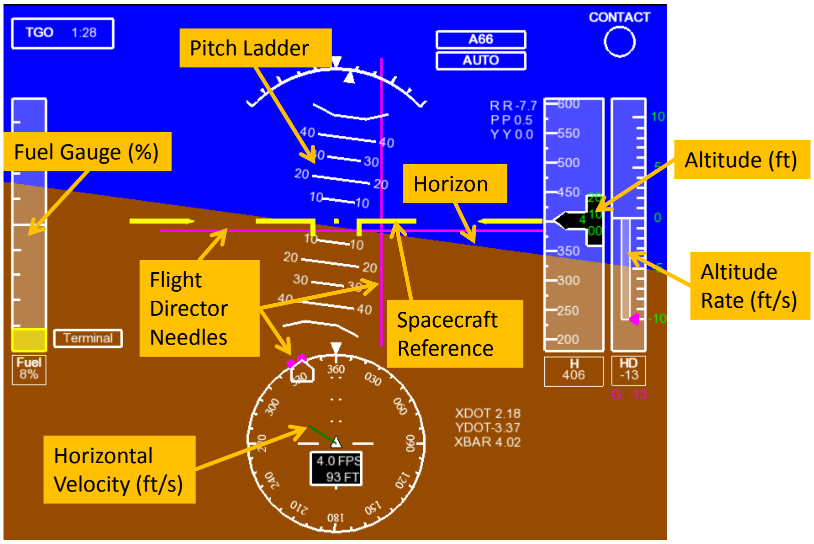
Displays

- Two displays will be provided
  - Primary flight display
    - Provides information about vehicle states, such as attitude, altitude, horizontal and vertical velocity
    - Provides flight director cues
    - Uses a simulated horizon; does not show out-the-window information
  - Landing Area display
    - Provides information about hazards and recommended landing aimpoints
    - Top down view of terrain
    - Will sometimes provide "energy contours" that show the achievable limit of the vehicle based on remaining fuel

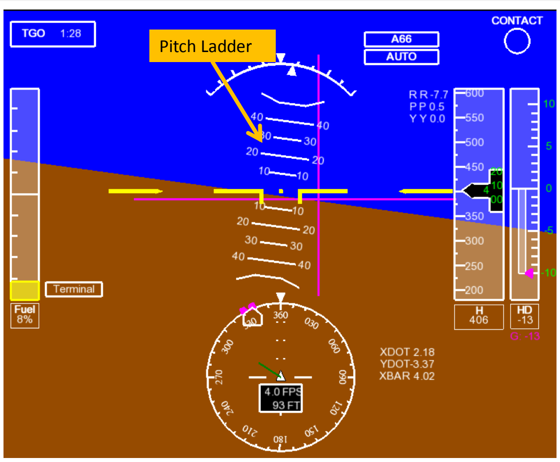




Displays – Primary Flight Display

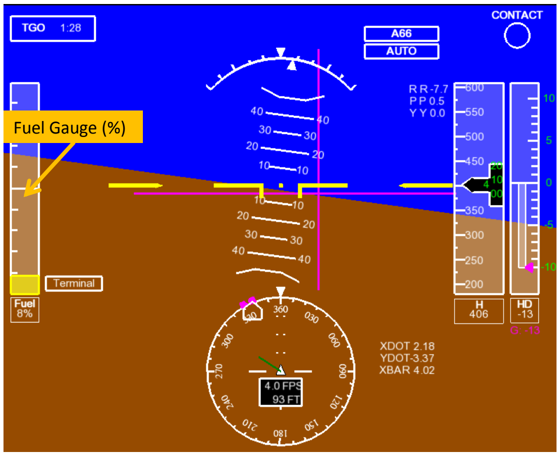


Displays – Primary Flight Display



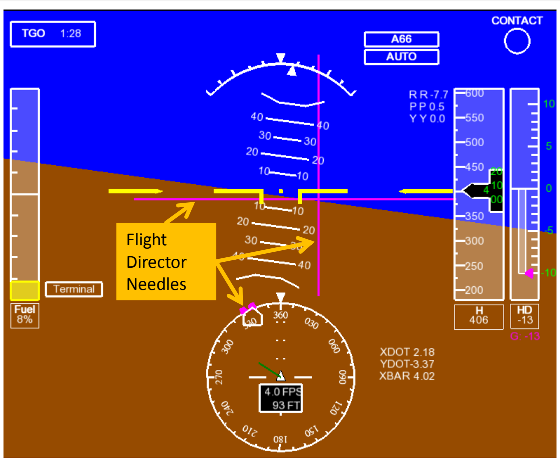
- The pitch ladder shows your current roll and pitch
- If the spacecraft indicator is below the horizon, it indicates you are pitched nose-downward (and above the horizon indicates pitched up)
- Roll is indicated by the slope of the horizon and the roll indicator arc at the top of the ladder

Displays – Primary Flight Display



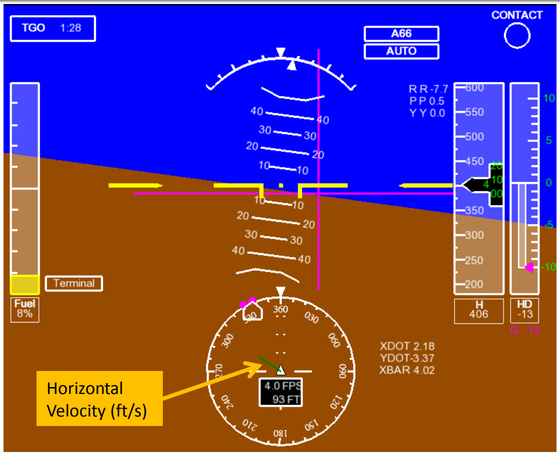
- The fuel gauge shows your current fuel in both graphical (bar) and numeric form
- Be aware that you start with only about 12% fuel, since it is assumed you have already performed the braking and approach phases
- BINGO fuel (which will be discussed further later) is at 2.4% fuel for your reference

Displays – Primary Flight Display



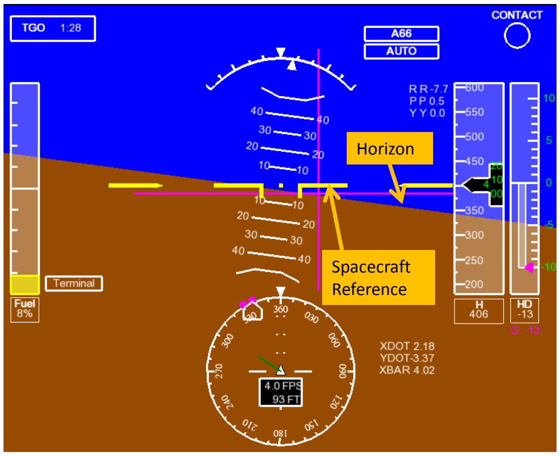
- The flight director needles indicate the desired attitude to follow the nominal landing trajectory
- The roll (vertical) and pitch (horizontal) magenta lines are in a “fly-to” format – meaning you want to bring them towards the yellow dot representing the spacecraft
- The heading flight director indicates the direction you would need to yaw to put the landing aimpoint directly in front of you

Displays – Primary Flight Display



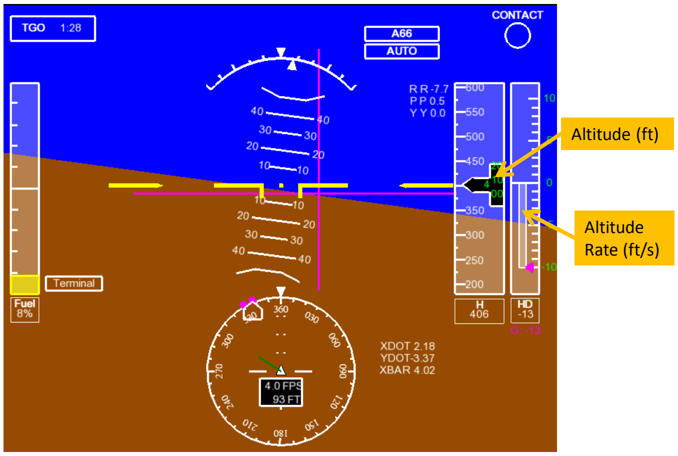
- The velocity vector (part of the horizontal situation indicator) shows the horizontal direction that the vehicle is travelling
- The compass is heading up, and note the "Doghouse" that represents the location of the landing aimpoint once you get within 100ft range
- The double dots show the scaling of the velocity vector
- There are two scales to the vector
  - Solid line = less than 10ft/s (dots indicate 2.5ft/s increments, to 10ft/s at outer edge)
  - Dotted line = greater than 10ft/s (dots indicate 5ft/s increments, to 20ft/s at outer edge)

Displays – Primary Flight Display



- The spacecraft reference shows the current attitude of the vehicle with respect to the pitch ladder
- You can use this reference along with the horizon to quickly judge attitude
- Note that attitude is also numerically displayed in the upper right corner by the altitude meter (R = Roll, P = Pitch, Y = Yaw)

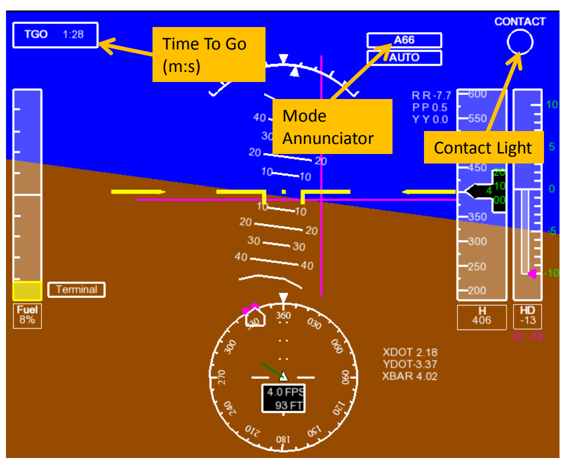
Displays – Primary Flight Display



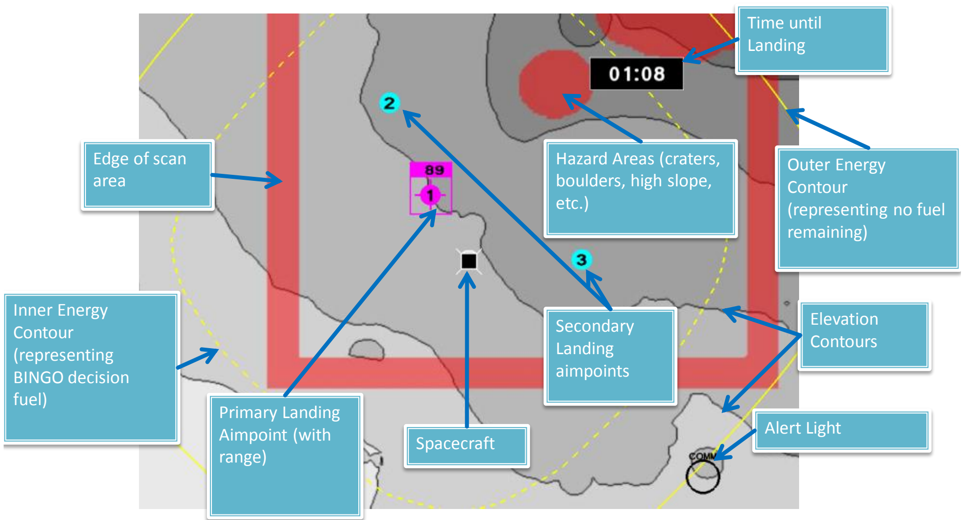
- Your altitude is represented both by the green number in the box on the tape as well as a numeric reading just below the altitude tape
- Altitude is judged in ft above the terrain
- Altitude rate is shown both as a bar and numerically below the bar

Displays – Primary Flight Display

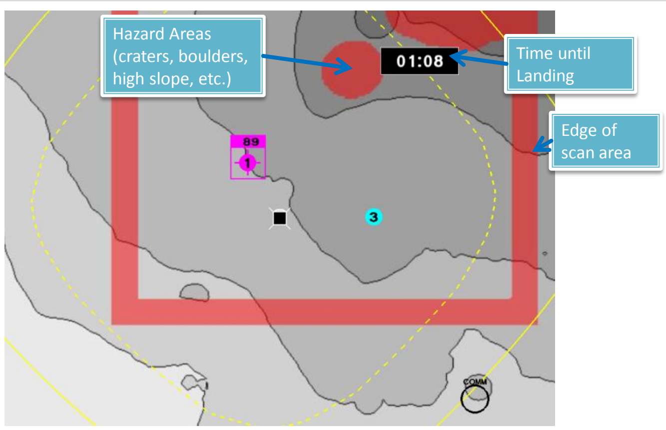
- Other notes
  - The Time To Go in the upper left shows you the estimated time to landing based on the nominal descent trajectory
  - You can use the Time To Go along with the BINGO fuel call (to be discussed further) to estimate fuel at landing
  - The mode annunciator shows the current control mode
    - A65 = Supervisory
    - A66 = 2-Axis Manual
    - AUTO = automatic vertical
    - HOVER = hover commanded
  - The contact light comes on about 10 ft above the terrain, indicating to you that touchdown is imminent



Displays – Landing Area Display

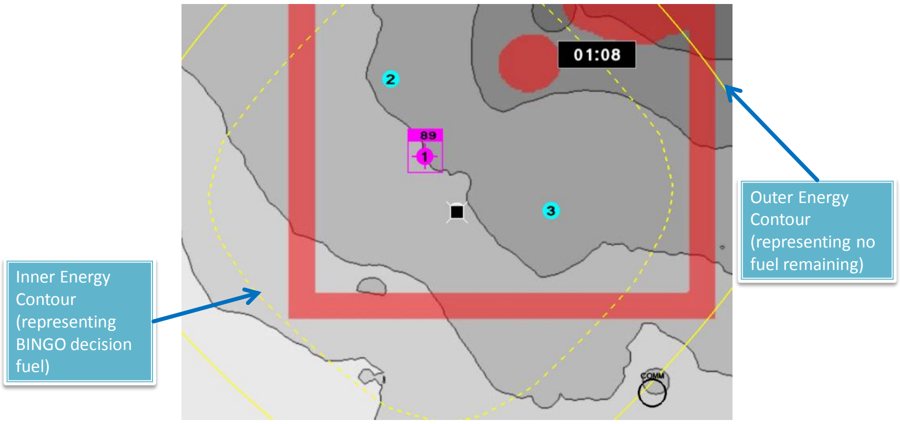


Displays – Landing Area Display



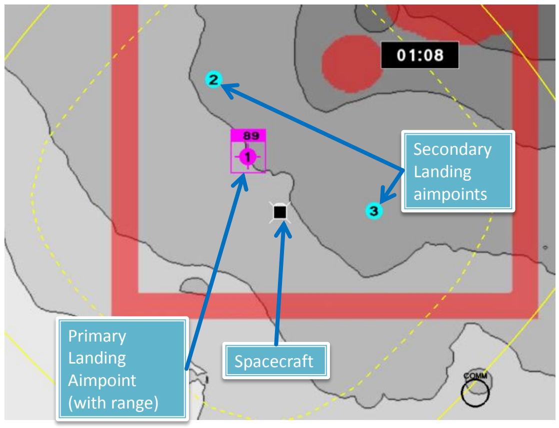
- Hazard areas are indicated by red on the map
- These are unsafe areas for landing based on an onboard algorithm that processes a scan of the terrain
- Note that the edge of the scan area is also considered hazardous
- For size reference, the outer box represents a 180x180m area (590x590ft)
- The Time until Landing box shows the same time that is shown in the Time To Go on the Primary Flight Display

Displays – Landing Area Display



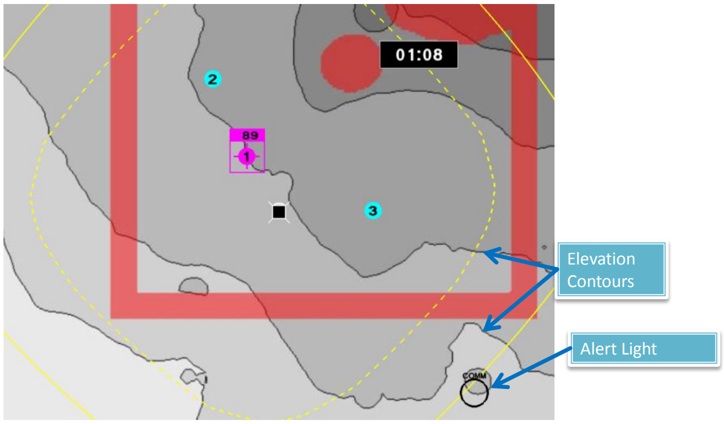
- The energy contours approximate the achievable landing area based on the current states of the vehicle
- There are two contours
  - The outer contour indicates that you could land within this area without running out of fuel
  - The inner contour indicates that you could land within this area with greater than BINGO fuel (2.4%)
- The closer the landing site to the center of the contour, the more estimated fuel at landing
- You can use the contours to select an appropriate alternate landing aimpoint at redesignation!

Displays – Landing Area Display



- The primary (currently selected) landing aimpoint is shown in magenta, with a text box showing range in ft
- Secondary landing aimpoints are shown in cyan
- If you redesignate to a new landing aimpoint, the newly selected aimpoint will become magenta, and the old one will turn cyan
- The spacecraft symbol is fixed on the screen, and the map moves/rotates around it
  - This means the display is "heading up"

Displays – Landing Area Display



- The elevation contours give you an idea of the relative elevation changes in the terrain
- The contours are done like a topographic map – closer together means steeper slope
- The contours represent 10ft elevation change
- The Alert Light indicates when a communication signal needs to be addressed – this will be discussed in more detail later

Displays – Auditory Display

- In some of the trials, you will not be given the energy contours as part of the landing area display
- Instead, you will have an auditory call-out to remind you how long you have until the “Bingo” time (as in Apollo)
- The Bingo time represents a measure of remaining fuel, and when reached indicates that you have only 20 seconds to land before you run out of fuel
- Play sample auditory call:

Other Communications

- At various intervals, ground control will request your attention (as designated by a lit “Alert” light on the landing area display)
- The “Alert” light will be transparent if you have attended to all requests, and will be either blue or green if your attention is needed
- It is your responsibility to attend to these requests
  - If the light is blue, press the #3 button on the top of the joystick
  - If the light is green, press the #4 button on top of the joystick
  - The light will turn off once you have pressed the appropriate button
- Try to attend to the requests as quickly as you can
- However, do NOT compromise your main task (following the flight director needles to land safely)… only address the alert light if it will not hinder your flying performance

Redesignation

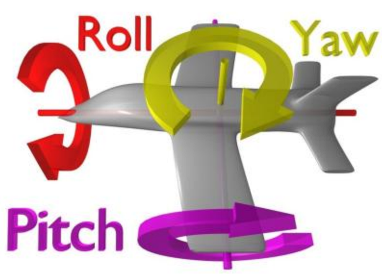
- In the descent to the lunar surface, a particular landing aimpoint may be judged as unsafe through out-the-window visual views of the lunar surface (out-the-window views are not provided for this experiment)
- However, to represent that possibility, a yellow “X” will show up over the currently designated landing site in the Landing Area Display to denote an unsafe landing aimpoint
- Watch for these symbols - if one comes up over your currently designated landing aimpoint, you must redesignate to an alternate aimpoint to safely land
- Remember that your goal is to land safely (low horizontal velocity, near-vertical attitude) while being close to the target and maximizing fuel remaining!

Redesignation

- Note that the ALHAT system assigns an order to the suggested landing aimpoints (#1,#2,#3), and this order indicates an order of preference
- This ordering relates to the relative safety of each landing aimpoint due to high slopes, proximity to hazards, or rough terrain
- Any choice to redesignate to a lower preference landing point should not be made lightly, and should consider this in addition to the touchdown parameters described earlier
- This includes required redesignations – the decision of which alternate landing aimpoint to choose should be carefully considered

Control Modes – Coordinate System Review

- There are three directions of vehicle rotation
  - Roll
  - Pitch
  - Yaw



- You can control all three of these axes, though flight director needles will only be given to you in roll and pitch

Control Modes - RCAH

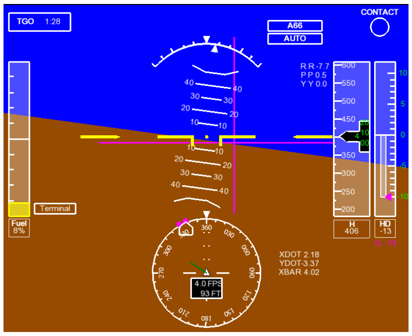
- The vehicle you will be flying utilizes a control scheme called “Rate Command / Attitude Hold” (RCAH)
- This means that your stick inputs control the rate of change of attitude of the vehicle, and bringing the stick back to center holds the current attitude (pitch, roll, and yaw)
- This is the same command mode that was used by the Apollo landers

Control Modes

- Two control modes will be used
  - Supervisory control mode – the automatic system will handle all vehicle motions with input from guidance and navigation algorithms, your only responsibility is to select a landing aimpoint and monitor the automatic system
  - Manual control mode – automation only directs vertical motion, you must pilot the vehicle in pitch, roll, and yaw, as well as select a landing aimpoint

Control Modes - Guidance

- Flight director needles will give you the required pitch and roll to achieve whichever landing aimpoint is currently your primary landing aimpoint (the needles will change if you switch primary aimpoints)
- Needles are in a "fly-to" flight director format
  - e.g if the needle crosshairs are above and right of the spacecraft symbol in the primary flight display, you need to pull the stick back (to pitch upward) and push it to the right
- There is also a heading indicator that shows which direction to yaw the vehicle to put the landing aimpoint in front of the vehicle
  - In the case to the right, you would need to twist the stick counter-clockwise to bring the landing aimpoint in front of the vehicle



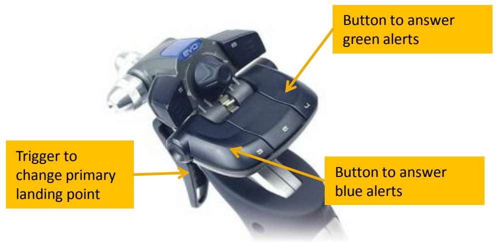
In this image, the pilot needs to push forward on the stick and push the stick to the right to meet the flight director needles

Controller

- There is one controller used, a joystick

Controller

- Fore-aft motion of the stick commands pitch (forward = pitch down), and left-right motion of the stick controls roll
- Use the trigger to cycle through landing aimpoints
- Use Buttons 3 and 4 on top of the joystick to respond to alert requests

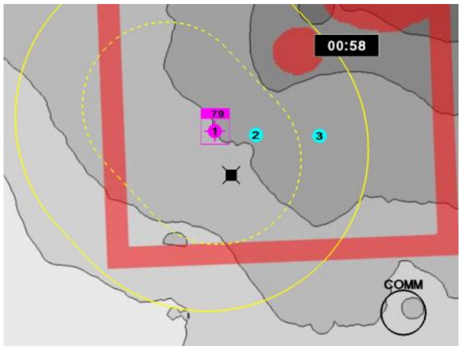


Strategies and Tips

- The energy contours can be very useful in determining the bestalternate landing aimpoint
  - The closer the alternate aimpoint to the center of the contours, the more fuel will be remaining on landing!
  - You can use the Bingo contour to judge the fuel at landing (bingo fuel represents 2.4% fuel remaining) – if the aimpoint is within this contour, you will have more than that remaining at landing, if you land outside, you'll have less
  - See next slide for demonstration
- The guidance will fully command the vertical descent of the vehicle
  - This means that during a redesignation, the automatic system may put you into a hover to avoid landing early
  - In order to continue the descent, you must pilot the vehicle above the desired landing aimpoint, and the automatic system will resume the descent
  - If you take a long time in getting to the new aimpoint, it will be very fuel expensive!

Strategies and Tips

- In this image, if you redesignate to #2, you'll land with greater than BINGO fuel
- If you redesignate to #3, you should still have enough fuel to land, but will have less than BINGO fuel remaining
- It's a good idea to monitor the contours and plan ahead on which aimpoint is a good alternate; you never know when you'll need to redesignate!
- In reality, the decision to redesignate would be based off of out-the-window views



SART

- At the end of each trial, you will be asked for ratings of situation awareness
- You are to give a rating from 1 (low) to 7 (high) for the following categories
  - Demand on attentional resources (instability, complexity, and variability of situation)
  - Supply of attentional resources (arousal, concentration, division of attention, and spare capacity)
  - Understanding of the situation (information quantity, information quality, familiarity of the situation)
- Note that high demand is bad, while high supply and understanding are good

SART

- SART is intended to rate your situation awareness
  - Remember that situation awareness does not necessarily correlate with your workload, nor does it necessarily correlate with your performance
  - Good situation awareness is typically represented by good knowledge and understanding of the current and future vehicle states, as well as significant attention denoted to all tasks at hand
  - In rating, situation awareness, try to think about how well you knew the states of the vehicle – some sample questions to ask yourself are below:
    - Did I know my horizontal velocity at the time of a redesignation?
    - Did I know which alternate landing aimpoint would result in the most fuel at landing?
    - Did anything happen during the trial that I didn't anticipate?

SART Descriptions

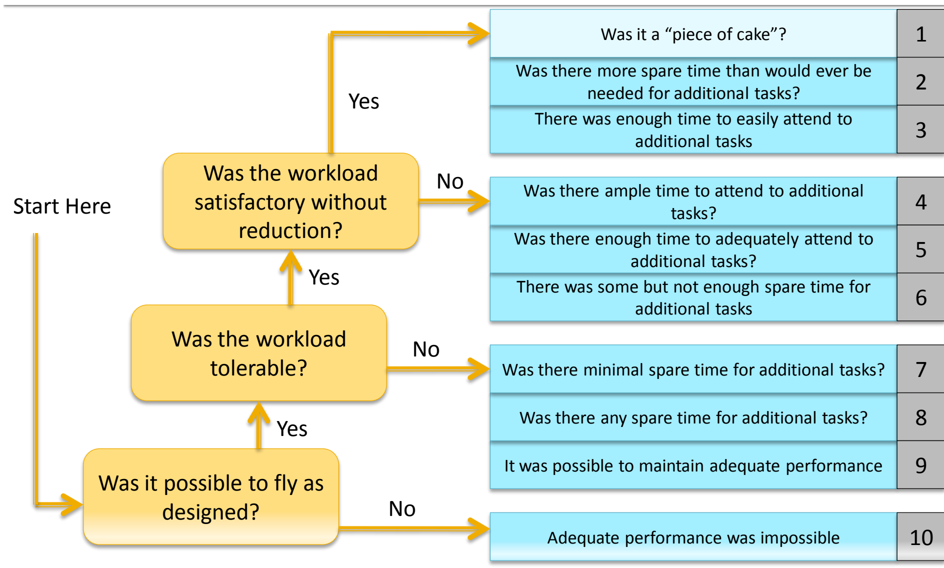
Rate these three

Category	Subcategory	Definition
Demand on Attentional Resources	Instability	Likeliness of situation to change suddenly
	Complexity	degree of complication of situation
	Variability	number of variables which require one's attention
Supply of Attentional Resources	Arousal	degree to which one is ready for activity (sensory excitability)
	Concentration	degree to which one's thoughts are brought to bear on the situation
	Division of Attention	degree of distribution or focusing of one's perceptive abilities
	Spare Capacity	amount of mental ability available to apply to new variables
Understanding of the Situation	Information Quantity	amount of knowledge received and understood
	Information Quality	degree of goodness or value of knowledge communicated
	Familiarity of the Situation	degree of acquaintance with situation, experience

Modified Bedford

- At the end of each trial, you will be asked to give a rating to the workload of the trial, using the Modified Bedford scale
- The scale goes from 1 (very low workload) to 10 (impossible)
- The next slide outlines how to determine a Modified Bedford rating
- Try practicing giving some ratings!

Modified Bedford



Recap

- Your goal is to choose an acceptable landing aimpoint and direct the vehicle to the surface
- Utilize information contained in both the primary flight display as well as the landing area display
- Redesignate the landing site if necessary, try to maximize fuel at landing
- There are 2 control modes
  - Supervisory control
  - Manual control
- At various intervals in the experiments, you will be asked to rate situation awareness and workload for the tasks

Practice

- You're ready to practice!
- Feel free to practice as much as you need to feel comfortable flying the vehicle

Appendix XII – Data by Dependent Variable

SART - Demand on Attentional Resources

Subject ratings of demand on attentional resources varied considerably, and are shown in Figure 20. The demand on attentional resources rating (as discussed in Chapter 2) should indicate the attentional resources required by the task, and therefore ideally should not vary greatly between subjects. The variation seen in Figure 20, however, indicates that the subjects were not using the same anchoring for their ratings. This underscores the limitations of using subjective scales for rating situation awareness, which will be discussed in further detail in Chapter 5. Subject 10 was an experienced pilot, and may have perceived the task as easier than other subjects did. Subject 8 had some limited simulator experience, but no flight experience and did not have experience flying lunar landing-type vehicle dynamics. Note that the SART ratings are on a 1-7 scale, and that subject 8 always rated the task at the highest demand on attentional resources level. This could indicate inadequate training or unusual scale anchoring for this subject.

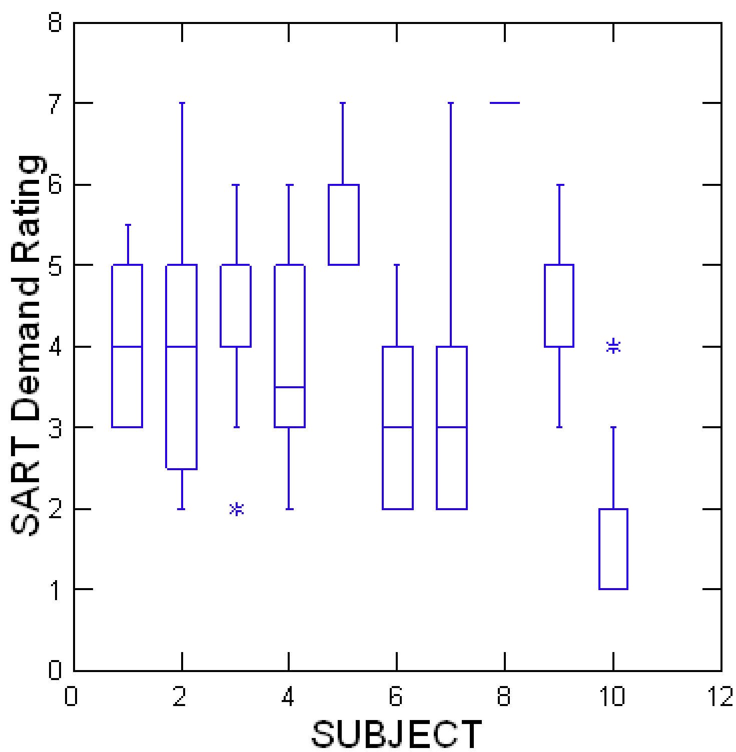


Figure 45. SART demand on attentional resources ratings by subject across all experimental conditions

The achievability contour display showed some effect on ratings of demand on attentional resources. Figure 21 shows the change in rating by subject for the achievability contour display as compared to the Apollo-style auditory display. A decrease is observed in the average ratings of demand on attentional resources with the use of the achievability contour display. This decrease was not significant based on a Friedman test (p = 0.096). This interaction should be examined in future experiments with an increased number of subjects.

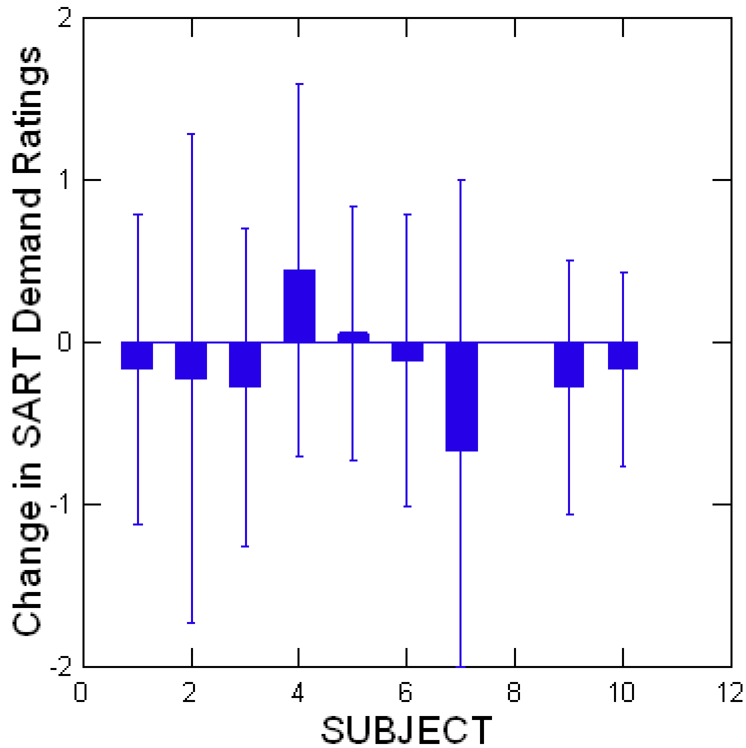


Figure 46. Display effect on SART demand on attentional resources ratings by subject (avg +/- std err, positive indicates higher ratings with contour display)

The effects of control mode and the presence of a required redesignation on SART demand ratings were also analyzed. Figures 22 and 23 show the change in SART demand ratings based on the use of manual control mode and required redesignations, respectively. Control mode showed an increase in SART demand ratings for most subjects, and this was statistically significant by a Friedman test ($p = 0.003$). Subject 8 differed in ratings from most of the subjects, but (Figure 19) rated demand on attentional resources the same across all conditions. There was an increase in SART demand ratings for both early and late redesignations as compared to the no-redesignation condition. This difference was significant for both the early and late redesignation conditions by Friedman test ($p < 0.0005$ for both). There was no significant difference by Friedman test between the early and late redesignation conditions.

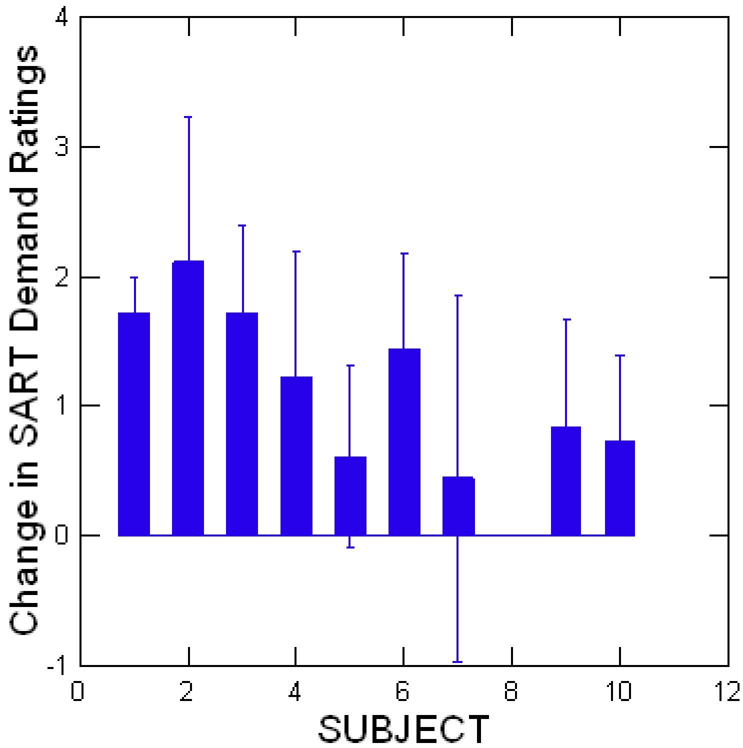


Figure 47. Control mode effect on SART demand on attentional resources ratings, by subject (avg +/- std err, positive indicates higher ratings with manual control)

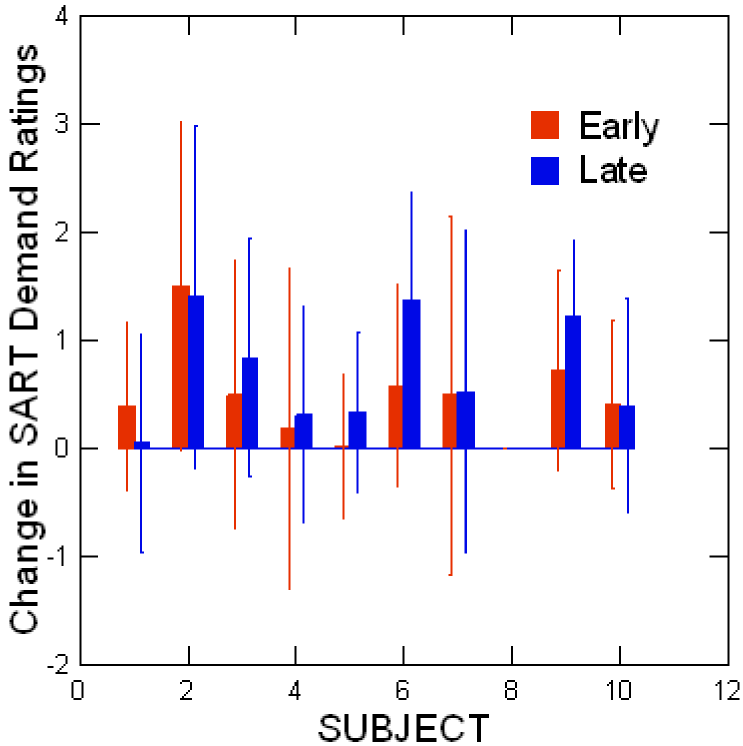


Figure 48. Redesignation effect on SART demand on attentional resources ratings, by subject (avg +/- std err, positive indicates higher ratings with redesignation as compared to none)

SART - Supply of Attentional Resources

Subject ratings of supply of attentional resources are shown in Figure 24. Subjects' ratings tended to agree more closely on ratings of SART supply than on ratings of SART demand. As discussed in Chapter 2, rating of SART supply of attentional resources addresses self-ratings of focus on the task. Most subjects consistently rated in the 5-6 range (on a scale of 7), which indicates that the subjects felt that they were devoting most of their attentional resources to the task. Subject 2 had no flight or simulator experience, and indicated some boredom with the task. This boredom likely corresponds to the lower self-rated focus to the experimental task.

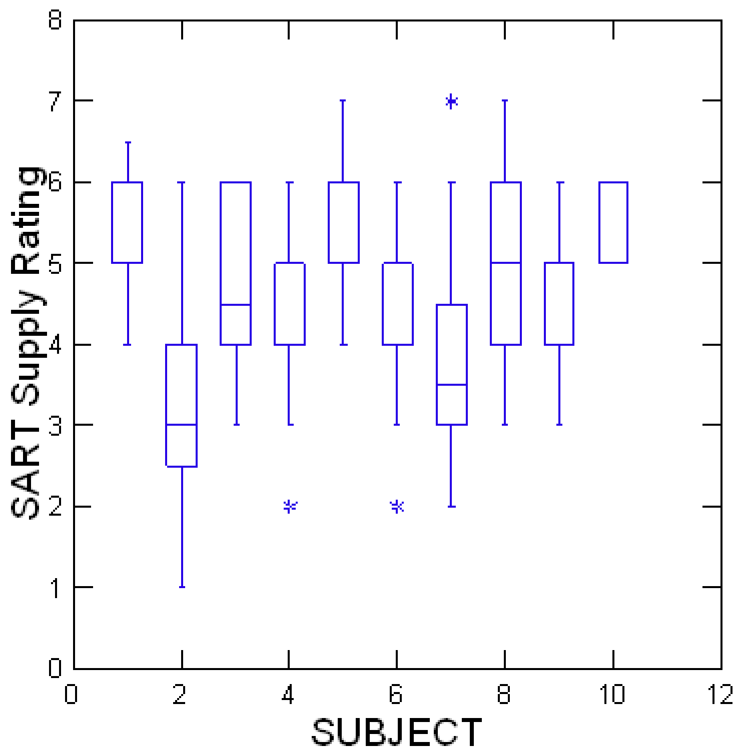


Figure 49. SART supply of attentional resources ratings, by subject across all experimental conditions

Analysis of the effect of the achievability contour display on SART supply ratings showed no consistent trends. This indicates that subjects did not feel that they were more focused on the task when provided with the achievability contours. Similar analysis was done to examine the effect of control mode and redesignation type on SART supply ratings. Figure 25 shows the effect of manual control (as compared to automatic control) on ratings of supply of attentional resources. A general increase is observed for most subjects in the manual control mode. Subjects were therefore more focused on the more challenging control case. However, this increase was not significant by Friedman test. Results based on redesignation type showed a similar effect on SART supply ratings (see Figure 26 below). There was a general increase in ratings with a required redesignation as compared to those without. This increase was significant for both the early and late redesignation as compared to the no-redesignation case in a Friedman test ($p = .005$ and $p < .0005$, respectively). There is also an increase in SART supply ratings seen between the early and late redesignation conditions, and this was found to be significant by Friedman test ($p < .0005$).

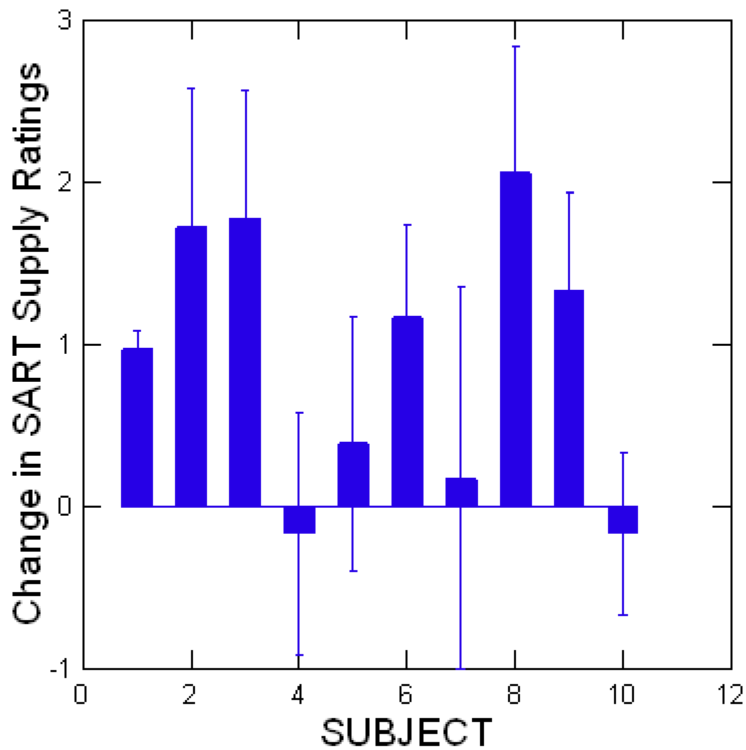


Figure 50. Control mode effect on SART supply of attentional resources ratings, by subject (avg +/- std err, positive indicates higher ratings with manual control)

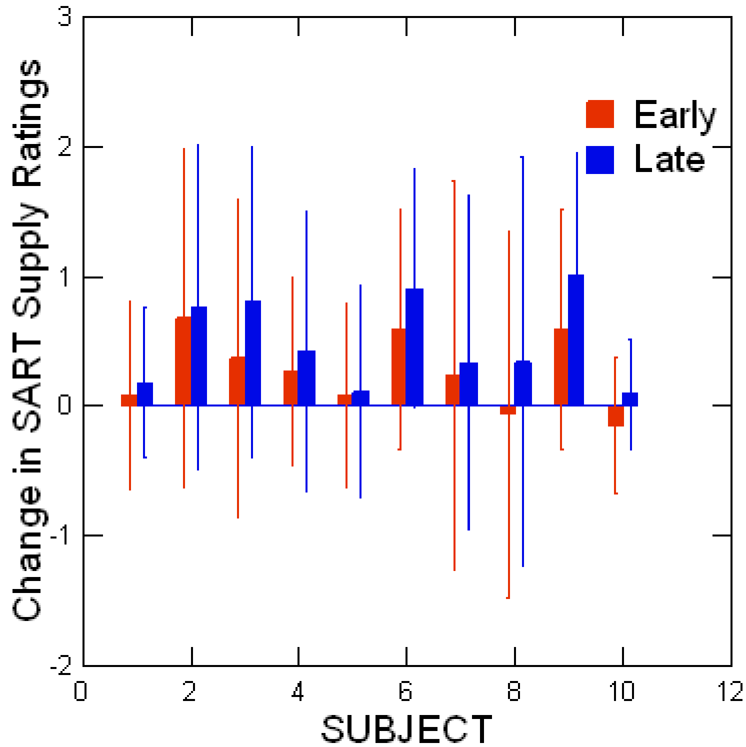


Figure 51. Redesignation effect on SART supply of attentional resources ratings, by subject (avg +/- std err, positive indicates higher ratings with redesignation as compared to none)

SART – Understanding of the Situation

Ratings of SART understanding of the situation varied by subject (Figure 27). Most subjects rated themselves consistently in the higher end of the SART scale (5-7 range). Subject 2 had no flight or simulator experience, and reported being unable to constantly monitor all of the important flight parameters. The outlying low points seen in Figure 27 correspond to cases where the subject temporarily lost control of the vehicle and ran out of fuel before landing.

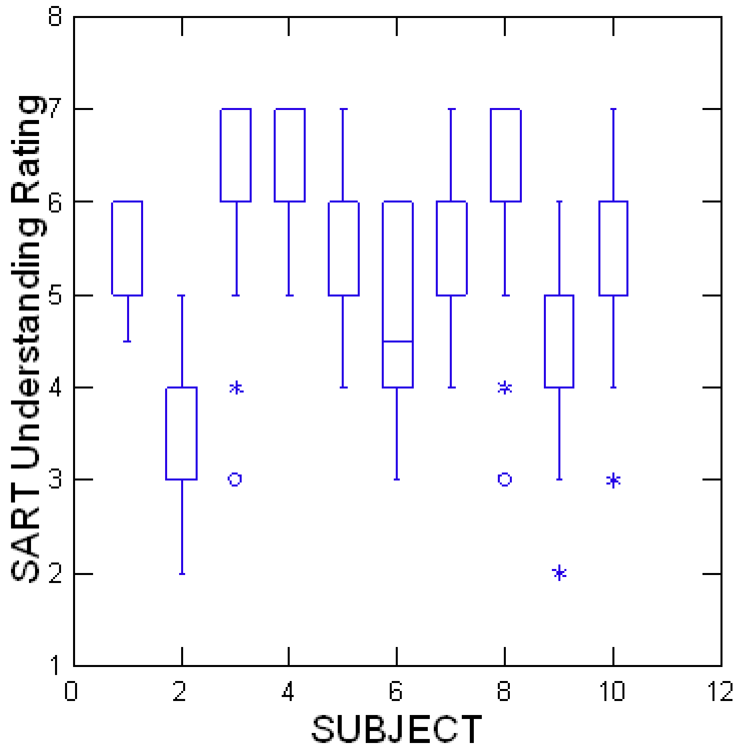


Figure 52. SART understanding of the situation ratings, by subject across all experimental conditions

The achievability contour display showed an effect on SART understanding of the situation ratings. Figure 28 shows the change in rating by subject for the achievability contour display as compared to the Apollo-style auditory display. An overall increase in ratings can be seen across all subjects, which was significant by Friedman test ($p = 0.003$). Subjects 3 and 8 showed very little change in ratings based on the achievability contour display, which may indicate that this type of display may differ in effectiveness based on the piloting and decision-making styles of the user.

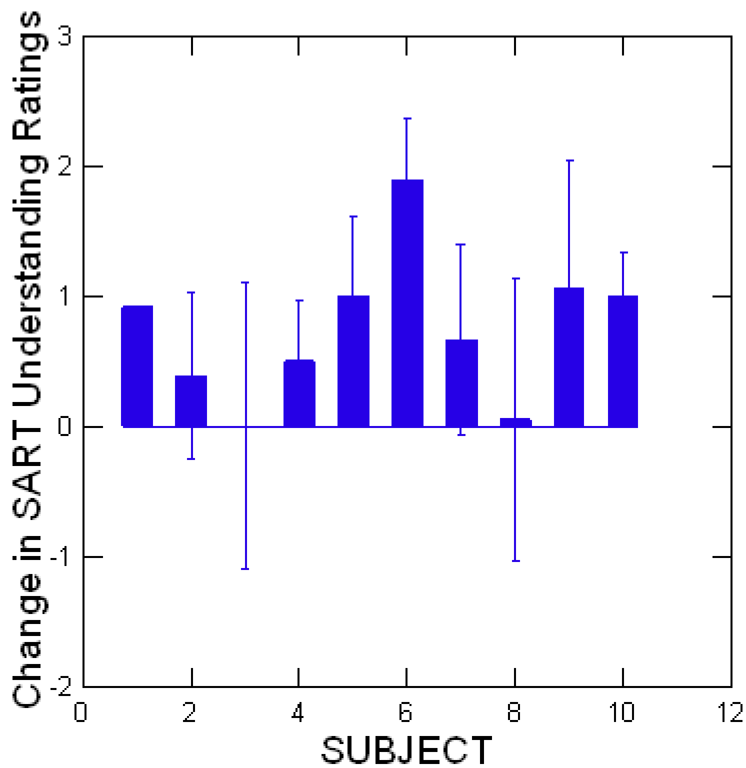


Figure 53. Display effect on SART understanding of the situation ratings, by subject (avg +/- std err, positive indicates higher ratings with contour display)

The ratings of SART understanding of the situation showed a significant effect of control mode (Figure 29) and redesignation type (Figure 30). The SART ratings in the manual control mode were significantly lower (Friedman test, p = 0.011) than in the automatic control mode. The variability in Figure 29, however, suggests that additional testing is needed to confirm this assertion. An overall decrease in understanding ratings is seen for both early and late required redesignations as compared to the no-redesignation case. As with control mode, there is considerable variability in the redesignation data (Figure 30), and further testing with increased definition of the scale values might help clarify the relationship. The decrease based on redesignation type was significant for both early and late redesignation conditions compared to the no-redesignation condition (Friedman test, p = .037 and p = .002, respectively), but there was no significant difference between the early and late cases.

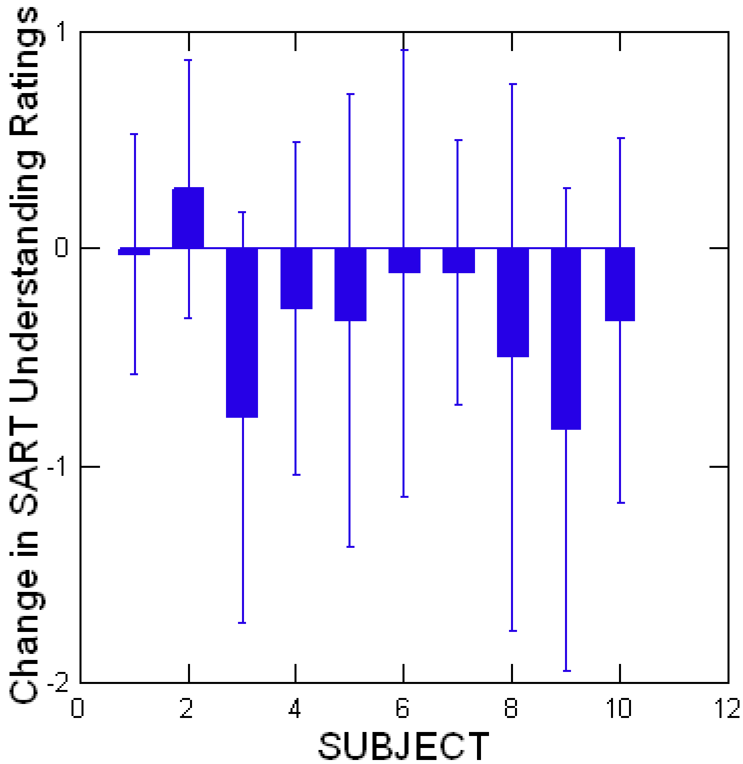


Figure 54. Control mode effect on SART understanding of the situation ratings, by subject (avg +/- std err, positive indicates higher ratings with manual control)

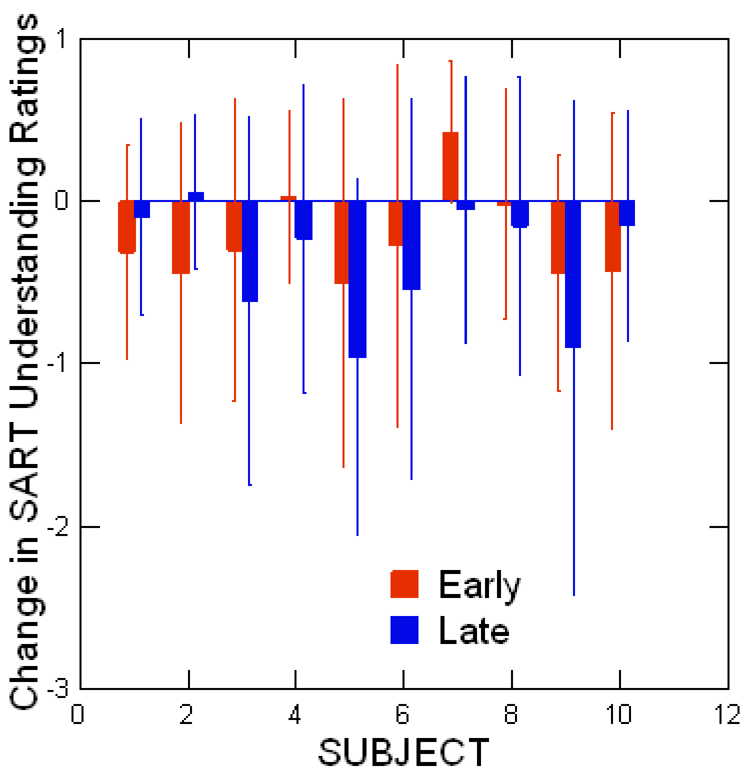


Figure 55. Redesignation effect on SART understanding of the situation ratings, by subject (avg +/- std err, positive indicates higher ratings with redesignation as compared to none)

Modified Bedford Scale

The Modified Bedford workload rating scale used for subjective workload showed considerable variation across subjects (Figure 31). The Modified Bedford scale provides a flowchart that helps subjects determine the appropriate rating for the situation. The subjects used the rating form in Appendix VII). There were varying opinions on the amount of spare workload capacity that could be devoted to additional tasks. There are several possible explanations for this difference. First, some subjects might be more skilled and therefore able to handle the primary and secondary tasks given without using much workload capacity. Second, the inherent workload capacity of the subjects may be different. Third, the subjects may not have been properly attending to all tasks (such as vehicle state monitoring during automatic control), and therefore had considerable remaining capacity. Demographic data provides some support for the first explanation. Subject 10 was a highly experienced pilot, and this could explain the low workload ratings. This single variable, however, does not fully characterize all the subjects' ratings. Subject 9 had considerable simulator experience, yet indicated less spare workload capacity than those of similar experience level. In the automatic control case, several subjects remarked on the relative ease of the tasks as a whole. This may indicate that the workload in the experimental tasks was not high enough to characterize workload definitively. This is discussed in Chapter 5.

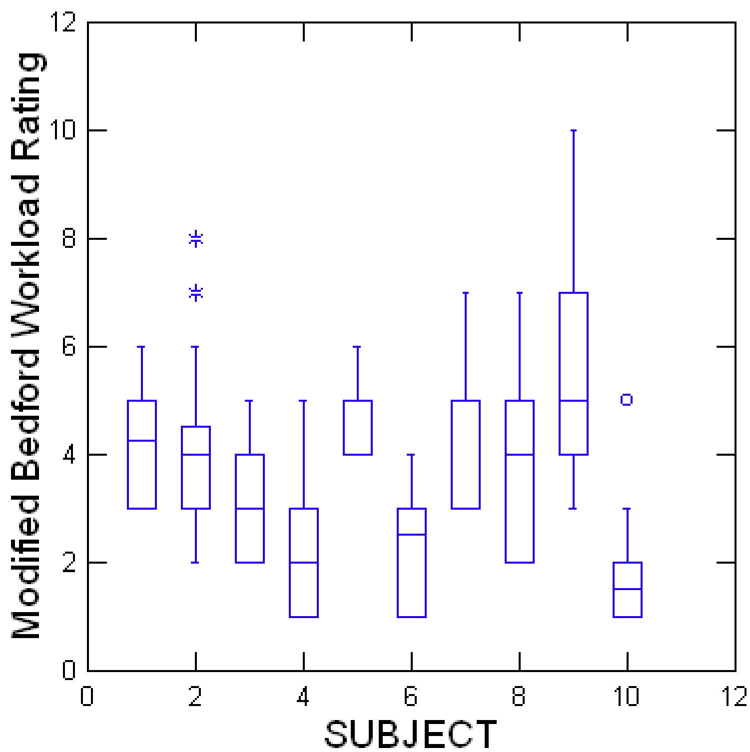


Figure 56. Modified Bedford workload ratings by subject across all experimental conditions

Subjects generally gave the achievability contour display lower workload ratings than the Apollo-style auditory display. That effect of display is shown, by subject, in Figure 32. The subjects agreed that the contour display gave smaller workload (Friedman test, $p = 0.011$). Although the errors are very large within each subject, the trend of the subject averages is clear, and significantly less than 0 by 1-sample Student t-test ($t = -4.390$, $df = 9$, $p = 0.002$).

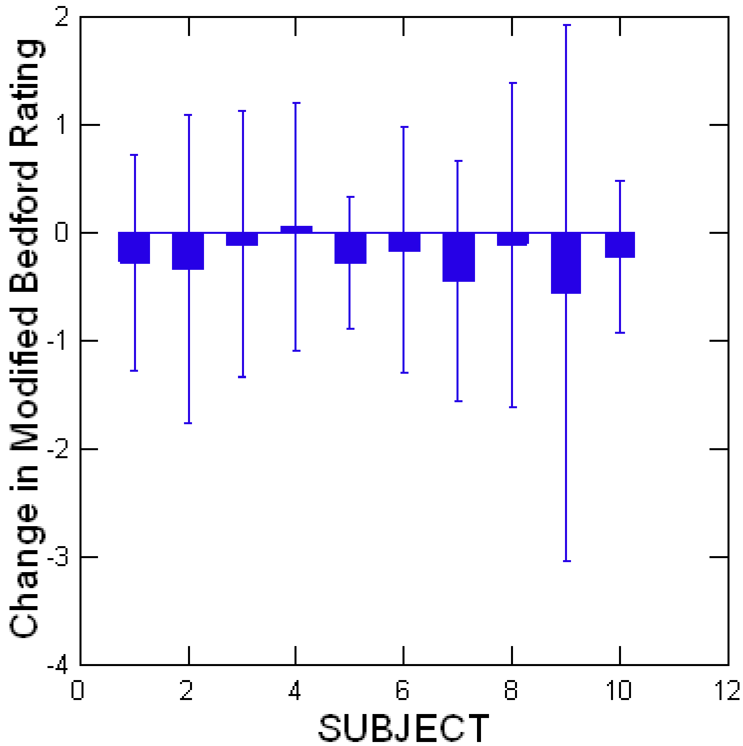


Figure 57. Display effect on SART understanding of the situation ratings, by subject (avg +/- std err, positive indicates higher ratings with contour display)

The effect (manual control - automatic control) of control mode on Modified Bedford workload ratings is shown in Figure 33. The workload is larger in manual control than in automatic control mode. This is not unexpected since the subject must track a larger number of vehicle states and guidance variables to complete the flight task successfully in manual rather than automatic mode. This increase was significant by Friedman test ($p = 0.011$).

Subject 7 reported no difference in workload between control modes. Since this same subject did not rate the tasks as either at the top or bottom of the workload scales in Figure 31, the most plausible explanation is that the subject found it difficult to assess workload. This weakness in subjective rating scales is discussed further in Chapter 5.

Requiring a redesignation also had an effect (increase) on Modified Bedford workload ratings, shown (Figure 34) for both early and late redesignations as compared with the non-redesignation condition. This effect was significant for both early and late redesignations by Friedman test ($p = 0.001$ and $p < 0.0005$, respectively). No significant difference was found between the early and late redesignation conditions themselves.

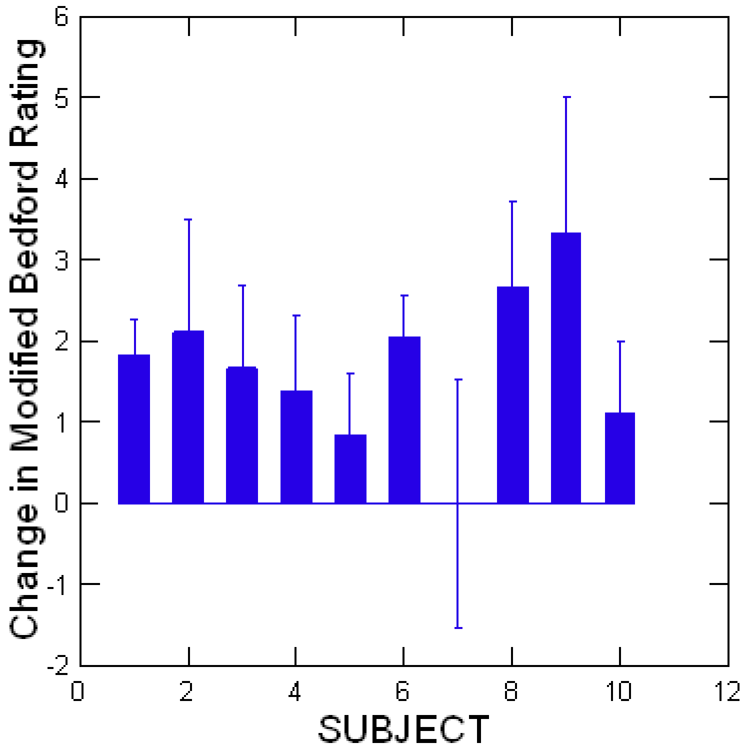


Figure 58. Control mode effect on Modified Bedford workload ratings, by subject (avg +/- std err, positive indicates higher ratings with manual control)

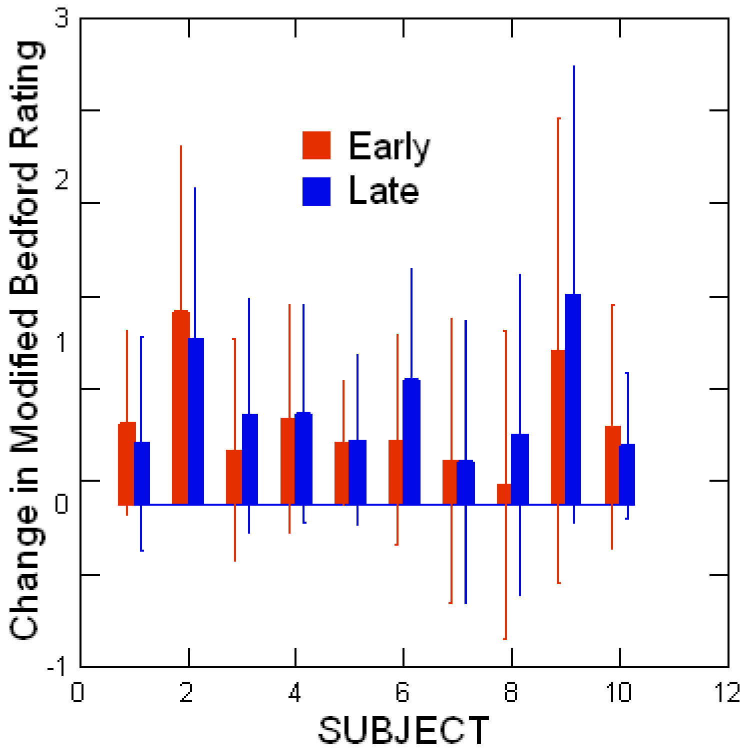


Figure 59. Redesignation effect on Modified Bedford workload ratings, by subject (avg +/- std err, positive indicates higher ratings with redesignation as compared to none)

Touchdown Range

The large differences among touchdown range performances across subjects (Figure 35) can be explained, in part, by differences in experience. Subjects 1 and 10, who were experienced pilots, gave consistently smaller (better) touchdown ranges than the other subjects. Subject 3 had no prior flight or simulator experience, and the decreased performance (larger range) may reflect that lesser experience. The same source can also account for subject 8's performance--some previous simulator experience, but not the familiarity with flying lunar landing-type vehicles in the simulator that many of the other subjects had. Subjects 2, 3, and 8 were the only subjects that had never flown this style of simulation before. Therefore, there may be a large training effect in this performance metric which suggests that future evaluations include increased training time in the simulator.

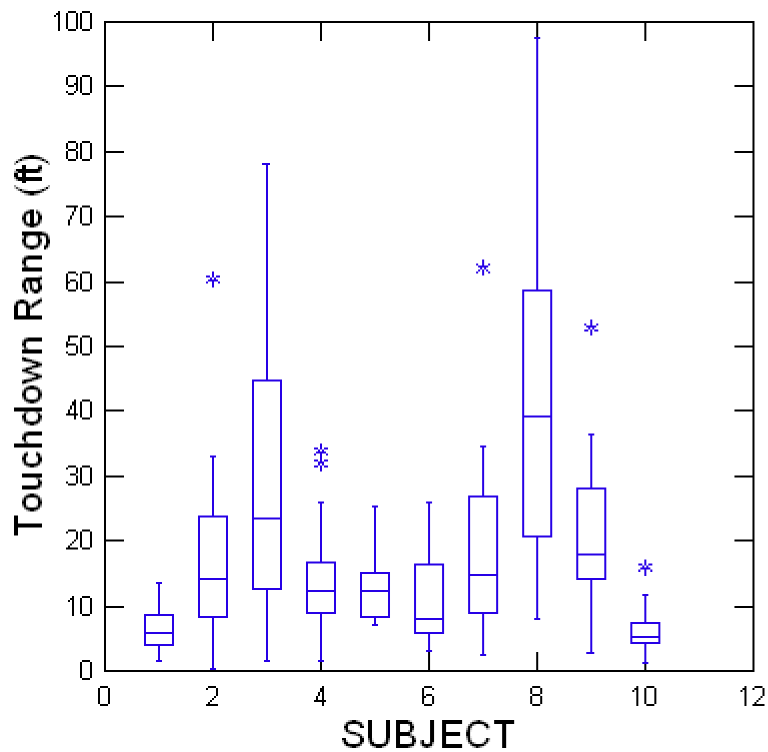


Figure 60. Touchdown range by subject, averaged over display and redesignation conditions

For the manual control mode cases, the data was investigated for effects of display and redesignation type. There were no consistent differences in touchdown range based on display type (Figure 36) and redesignation type (Figure 37). This is likely due to the design of the vertical guidance algorithms. In the vertical guidance (as described in Chapter 3), the vehicle hovered if the altitude was below 150ft and the range was greater than 100ft. Therefore, even with a redesignation, the guidance would wait until the subject had brought the vehicle above the new target landing site before descending. Therefore, the presence and timing of a redesignation would be expected to have little impact on the range from the landing target at touchdown.

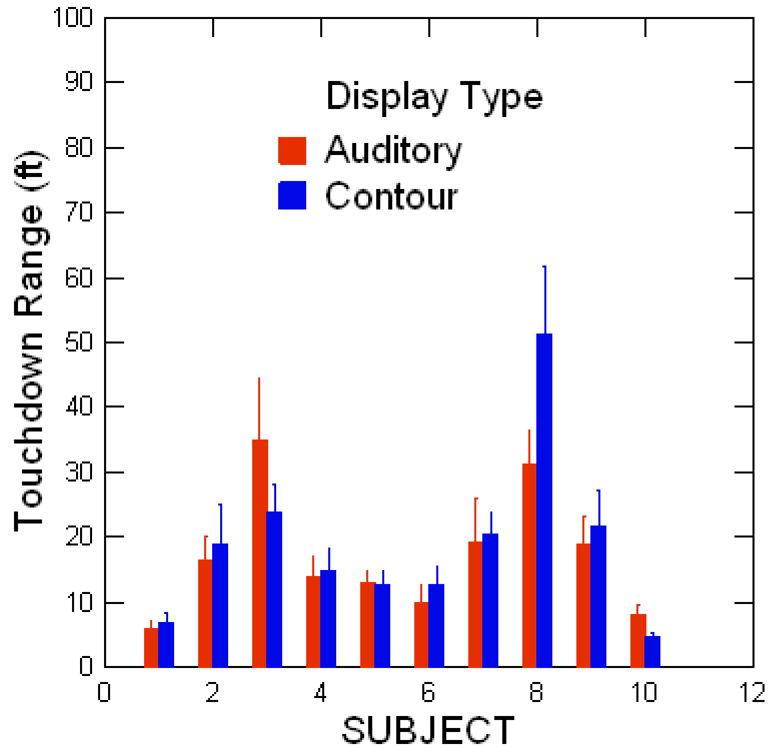


Figure 61. Touchdown range by subject for each display condition (avg +/- std err)

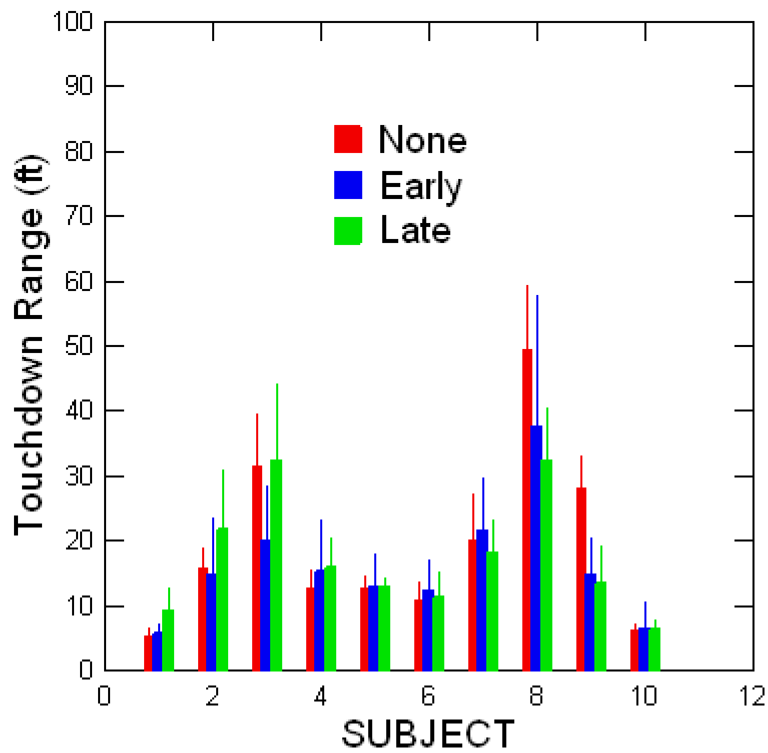


Figure 62. Touchdown range by subject for each redesignation condition (avg +/- std err)

Touchdown Attitude

The touchdown attitude deviation from the vertical by subject under manual control is shown in (Figure 38), averaged over all display and redesignation conditions. As with touchdown range, it appears that experienced pilots control touchdown attitude better than inexperienced pilots. The inexperienced subjects (other than 1 and 10) showed no large variations in performance from subject to subject. (There were some outlier landings). Since the vehicle guidance required a vertical descent down to the target landing point, there was typically a period of time during the final descent where the subject was responsible for tracking the guidance cues to maintain the vertical descent. Landing with a large touchdown attitude indicates that these subjects stopped following the guidance cues carefully and let the vehicle drift as it descended to the surface. This is corroborated by the touchdown velocity analysis below.

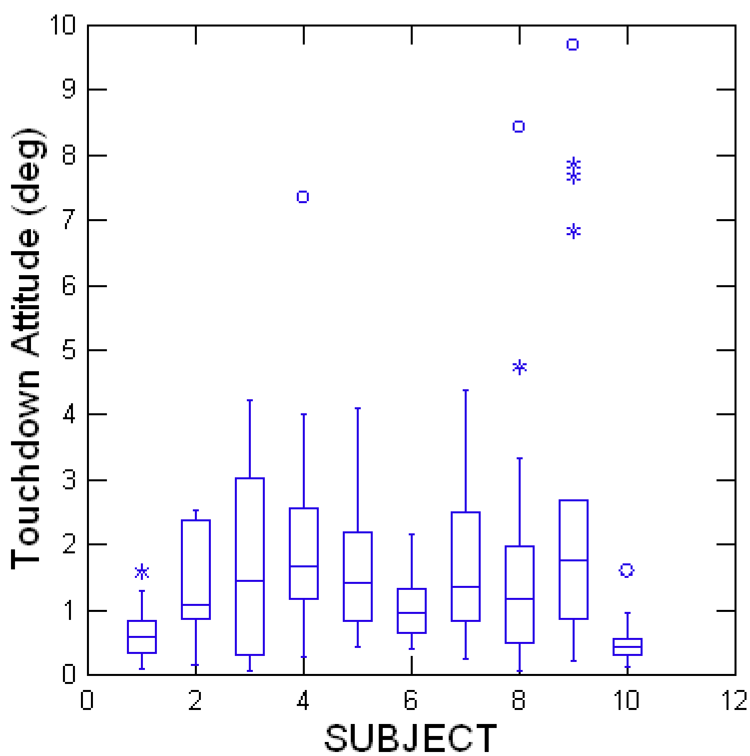


Figure 63. Touchdown attitude by subject averaged over all display and redesignation conditions

Touchdown attitude by display type and redesignation type are shown in Figures 39 and 40, respectively. A logarithmic transformation was performed for regression model analysis. A hierarchical mixed regression model was constructed with main effects of display and redesigation types for log(touchdown attitude). Neither effect was significant. In Figure 40, subjects 4 and 9 had higher touchdown attitudes for early redesignations than for either the late redesignations or for the no-redesignation cases. These effects are inconsistent, and there is sign of a significant effect of redesignation.

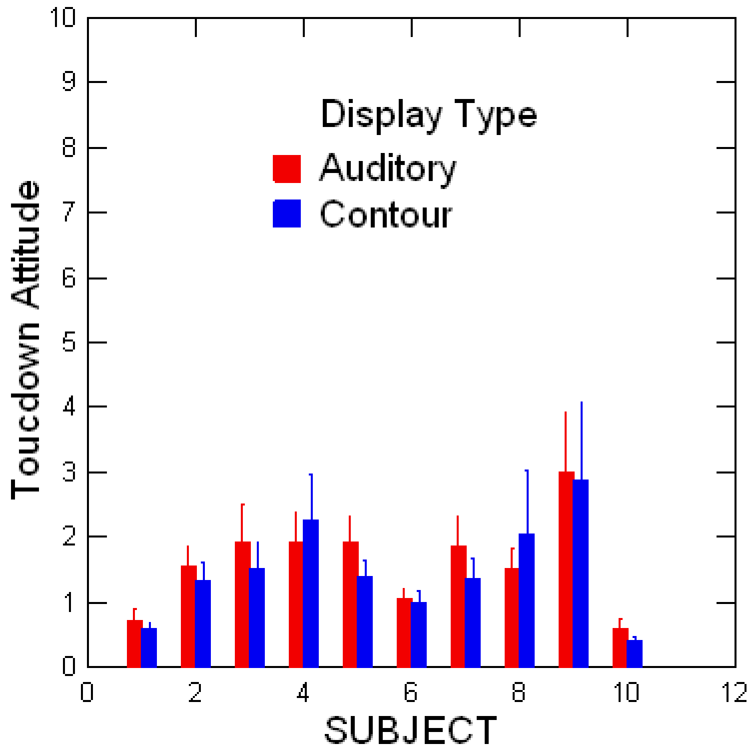


Figure 64. Touchdown attitude by subject for each display condition (avg +/- std err)

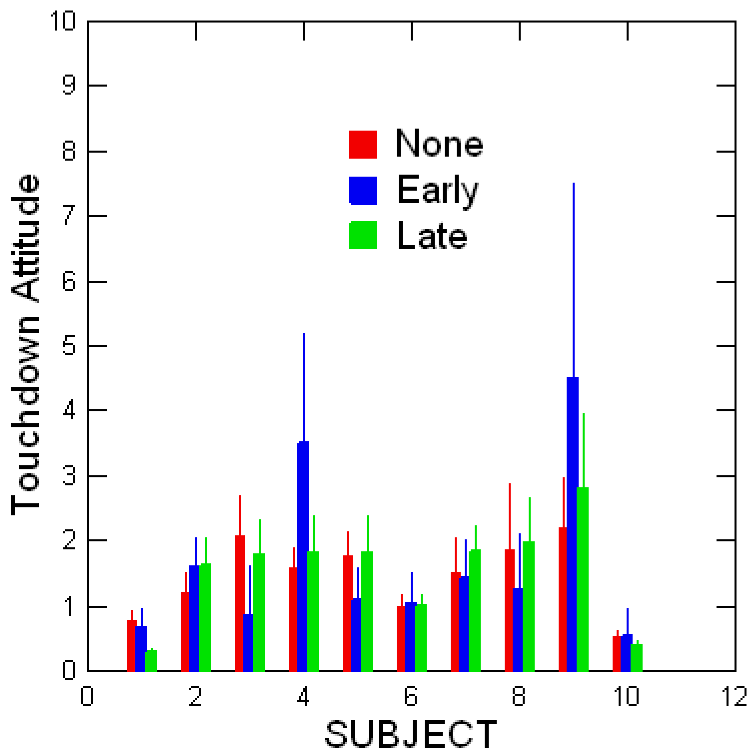


Figure 65. Touchdown attitude by subject for each redesignation condition (avg +/- std err)

Touchdown Horizontal Velocity

As was true of touchdown range and attitude, the increased piloting experience of subjects 1 and 10 apparently contributed to their superior performance in delivering low touchdown velocity (Figure 41). Subjects 3, 8, and 9 showed higher touchdown velocities than the other subjects. This supports the conclusion that these subjects allowed the vehicle to drift as it descended to the landing target. Further discussion of the touchdown velocities and their impact on the safety of the vehicle is included in Chapter 5.

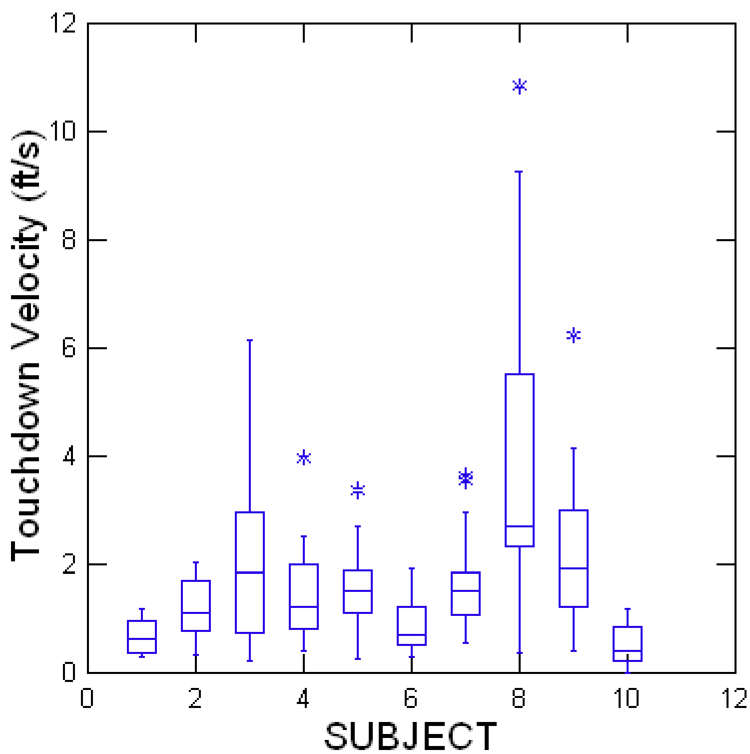


Figure 66. Touchdown velocity performance by subject averaged over all display and redesignation conditions

Touchdown velocity (Figures 42 and 43) was transformed to its logarithm for analysis against display type and redesignation. A hierarchical mixed regression model was analyzed against main effects of display type and redesigation type. Neither showed a significant effect.

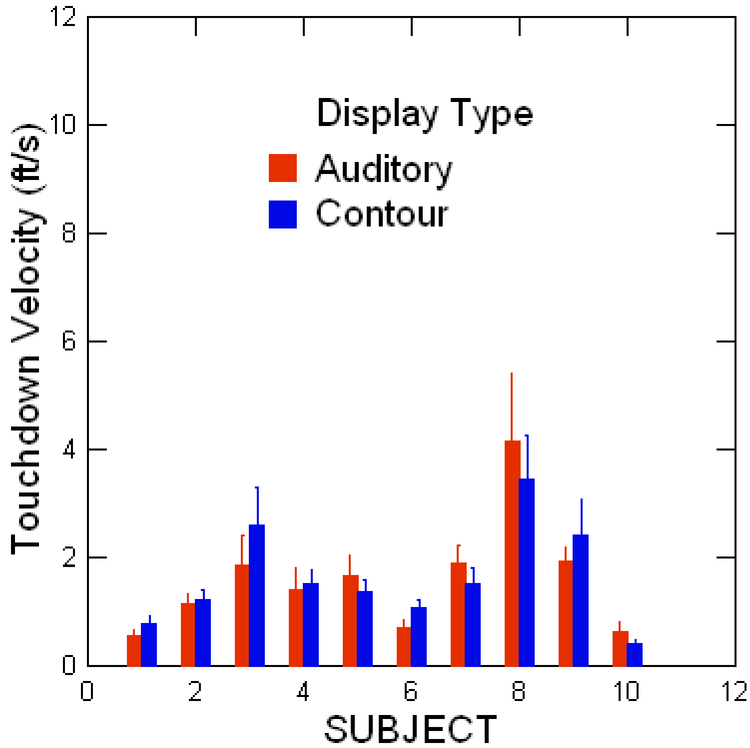


Figure 67. Touchdown velocity by subject for each display condition (avg +/- std err)

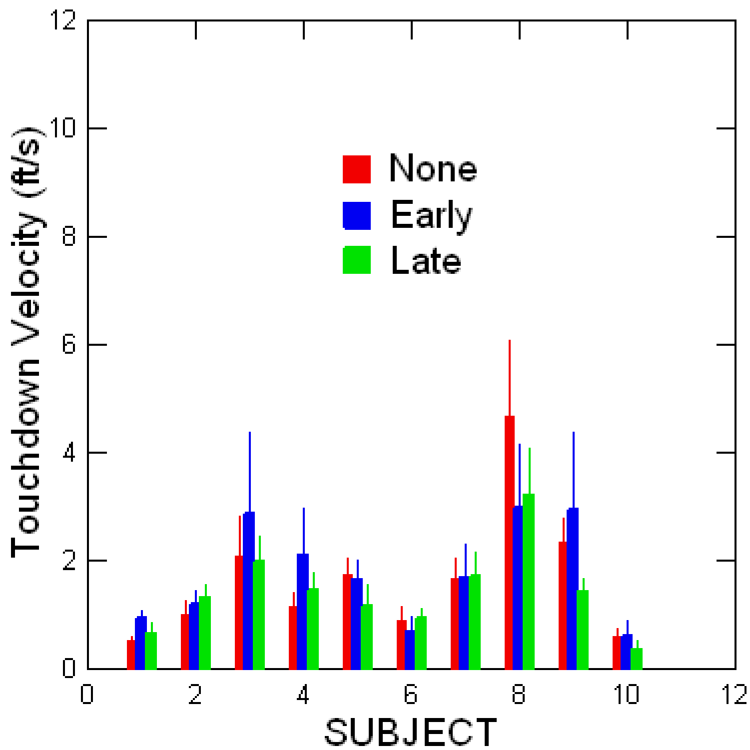


Figure 68. Touchdown velocity by subject for each redesignation condition (avg +/- std)

Touchdown Fuel

The effects of experience seen on touchdown range, touchdown attitude, and touchdown velocity are not seen on touchdown fuel data for manual control trials (Figure 44). Several subjects landed with zero fuel, which is a "crash" case. There were 6 trials (counting all subjects) in which the landing occurred with zero fuel. All of these cases were in manual control, and all but one required a redesignation. Typically these resulted from loss of control of the vehicle in a pilot-induced oscillation (PIO), in which the fuel spent in recovering control of the vehicle exceeded the fuel margin for landing at the intended target.

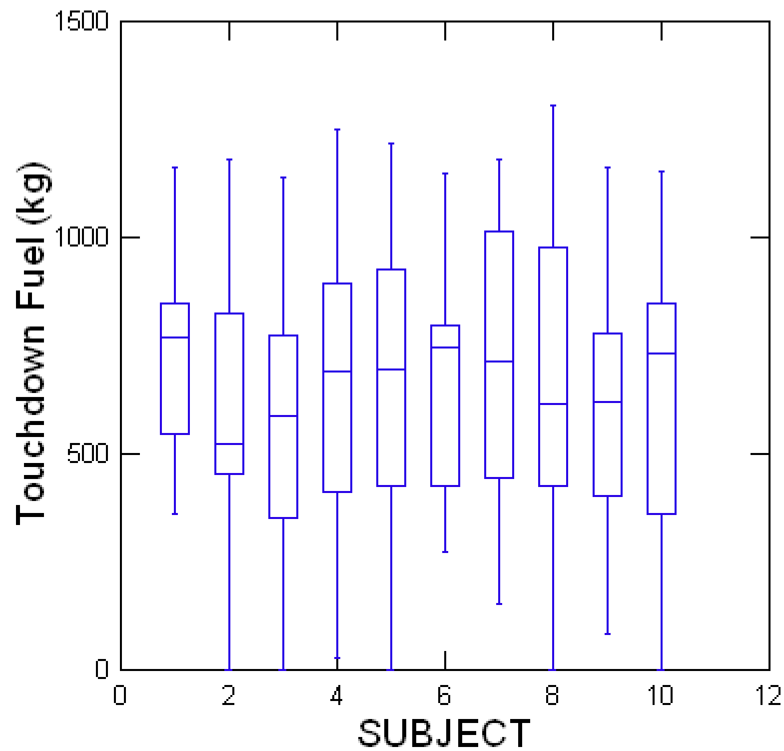


Figure 69. Touchdown fuel by subject, averaged over all display and redesignation conditions

The maps tested in the experiment differ in the location of the initial landing target and of the landing alternatives, and those features have an effect on fuel remaining at touchdown. Figures 45a,b,c, show respectively, the fuel remaining at touchdown for no-redesignation, early redesignation, and late redesignation trials. Within each plot, the fuel remaining (averaged over all subjects and display conditions) is plotted against map type.

The starting vehicle position is the same on every map, but the targets (landing aimpoints) are different. The initial target for map 4, for example, is farther from the starting vehicle position than in map 5. A mixed model hierarchical regression was analyzed against main effects of display and redesignation. The cross effect was also tested, but was determined to not contribute to the model fit. Touchdown fuel by display type and redesignation type are shown in Figures 46 and 47, respectively. The results of the model construction are listed below:

Variable	Estimate	Standard Error	Z	p-value
Subject	614.163	17.064	35.993	0.000
Auditory Display	32.111	13.910	2.308	0.021
No Redesignation	262.747	18.769	13.999	0.000
Early Redesignation	-12.830	22.188	-0.578	0.563
Late Redesignation	-249.917	20.239	-12.348	0.000

Table 5. Mixed Model Hierarchical Regression Results for Touchdown Fuel

These results show that subjects land with significantly less fuel (-32.111) below the overall average when they are using the achievability contour display. We expected the opposite, since that display was intended to make them more aware of fuel usage. This could indicate that the subjects were more confident in selecting a higher ranked point that is father away with the fuel contours. It also suggests that the subjects may have been more conservative in selection with respect to fuel when using the auditory display. This result is discussed further in Chapter 5. As might be expected, the effect of redesignation is significant and graduated in the expected direction, (no, early, late) redesignation in decreasing order (Figure 47).

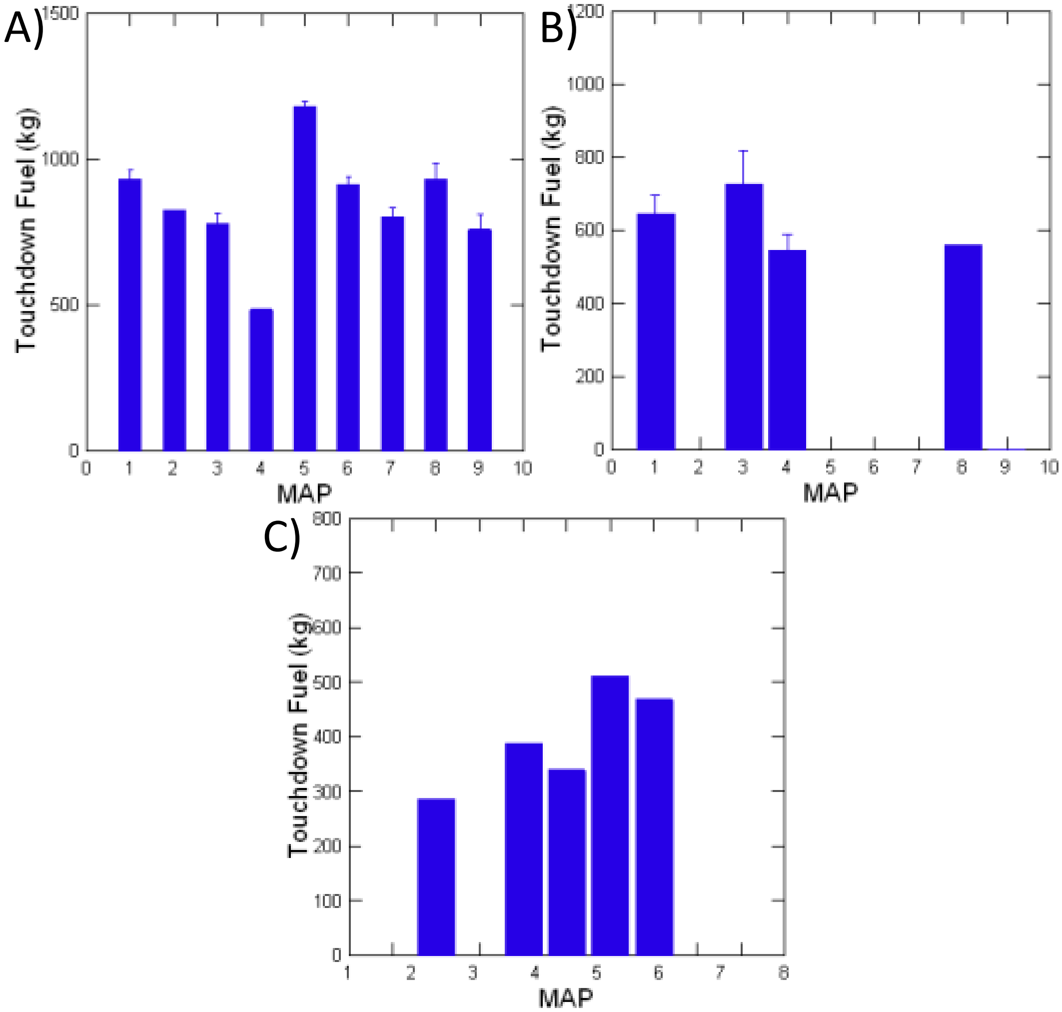


Figure 70a,b,c. Touchdown fuel by map for each redesignation type. Trials with (no, early, late) redesignation are shown in (a, b, c), respectively. Some map configurations were omitted from the experiment.

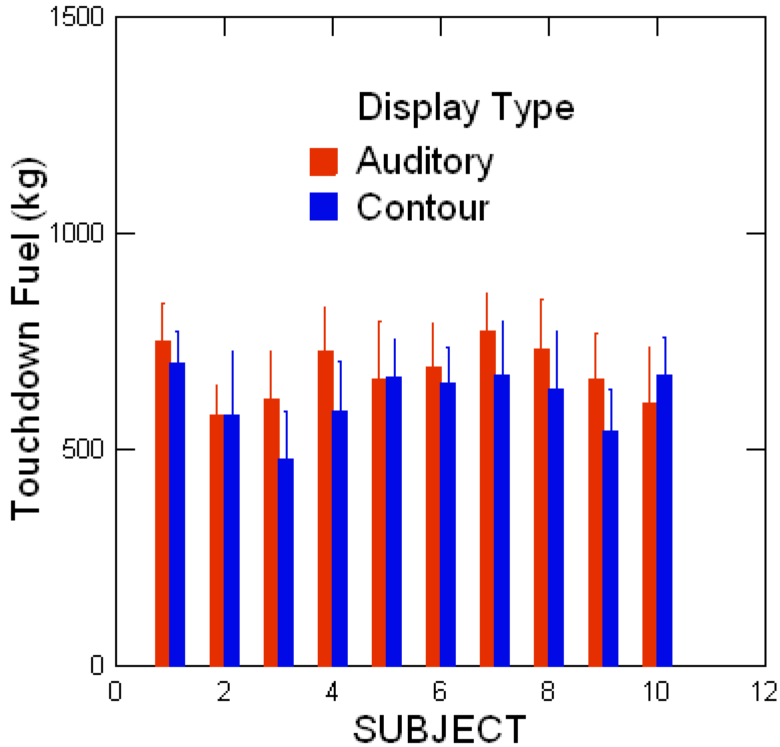


Figure 71. Touchdown fuel by subject for each display condition (avg +/- std err)

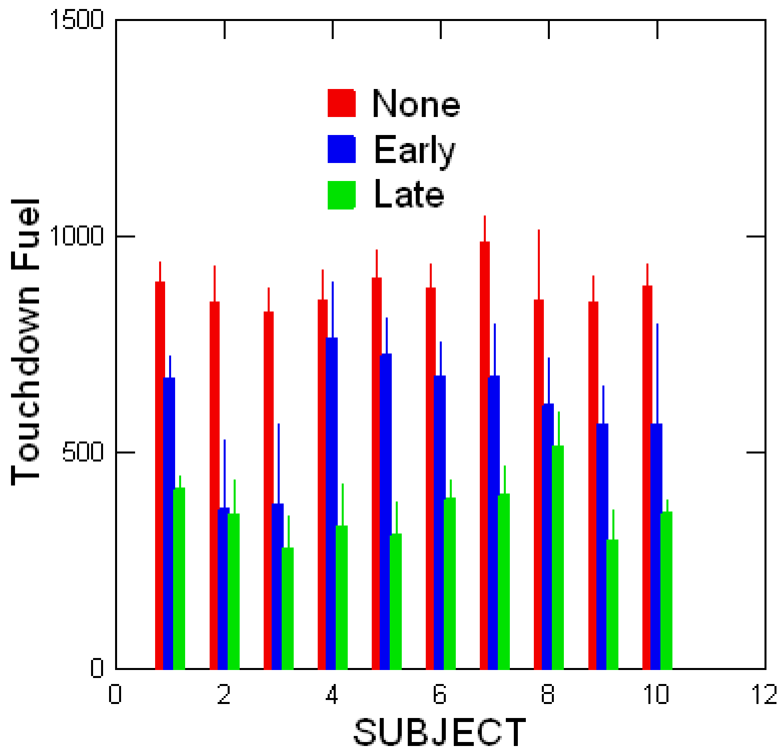


Figure 72. Touchdown fuel performance by subject for each redesignation condition (avg +/- std err)

Tracking Mean Square Error (MSE)

The quality of flight performance was measured by the mean square deviation (error) between the actual vehicle and the guidance recommended combined pitch and roll attitude. The redesignation portions of the trajectory (as defined in section 3.32) were removed to eliminate transients and to allow coherent comparisons to be made. This is discussed in Chapter 3. Subjects' quality of performance was highly variable. The high performers (subjects 1,10,6, in order of performance) in touchdown parameters also show good flight performance as measured by MSE (Figure 48). There are many outlier trials in several subjects, and most of these occur when the subject is not attending to the attitude guidance task. This could result from focusing on a single axis of control, from letting the vehicle “drift” during the terminal descent, or from focusing on the redesignation decision. Subject 8 differed in behavior from the other subjects in thinking that the guidance was too conservative. As a result this subject had intentionally large deviations from the guidance cues in order to close with the target landing point faster. This contradicted the instruction that performance was to be implemented by tracking the guidance cues.

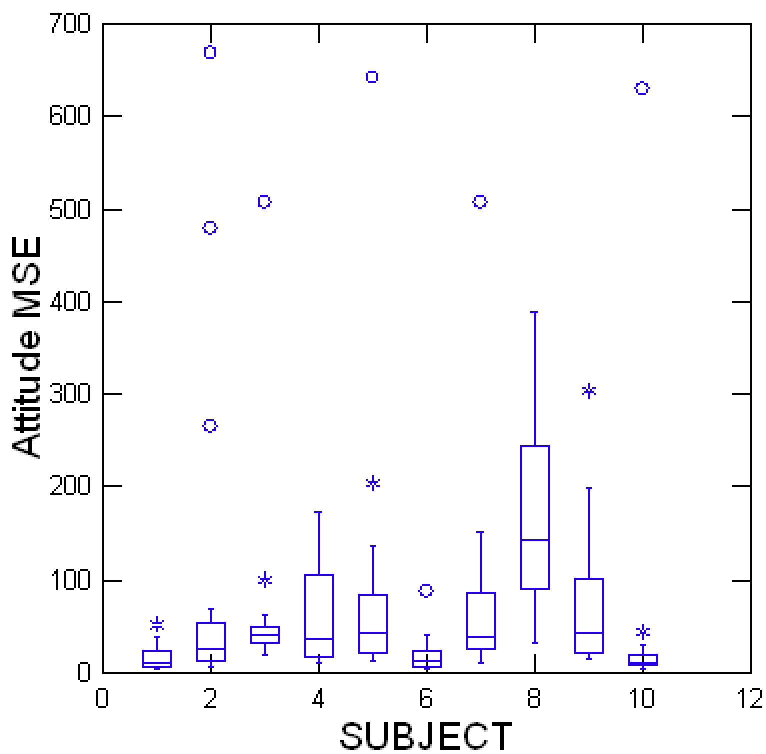


Figure 73. Attitude mean square error by subject across all display conditions

A mixed model hierarchical regression was constructed with main effects of display and redesignation. The cross effect was also tested, but was determined to not contribute to the model fit. Attitude MSE by display type and redesignation type are shown in Figures 49 and 50, respectively. Results of the model construction are listed below:

Variable	Estimate	Standard Error	Z	p-value
Subject	83.293	13.252	6.285	0.000
Auditory Display	4.424	7.736	0.572	0.567
No Redesignation	-49.854	10.439	-4.776	0.000
Early Redesignation	40.433	12.344	3.275	0.001
Late Redesignation	9.421	11.266	0.836	0.403

Table 6. Mixed Model Hierarchical Regression Results for MSE

The model indicates that the achievability contour display had no influence on flight performance, but the redesignation type does. There are significant differences between all of the redesignation types, with no redesignation associated with the lowest MSE, late redesignation with the middle MSE, and early redesignation with the highest MSE. This lends credence to the last explanation for an increased MSE listed above, where the subject ignores the flight task while making the redesignation decision. An early redesignation would allow for more available time to make the decision, and is supported by the number of redesignations analysis below in the decision-making behavior analysis.

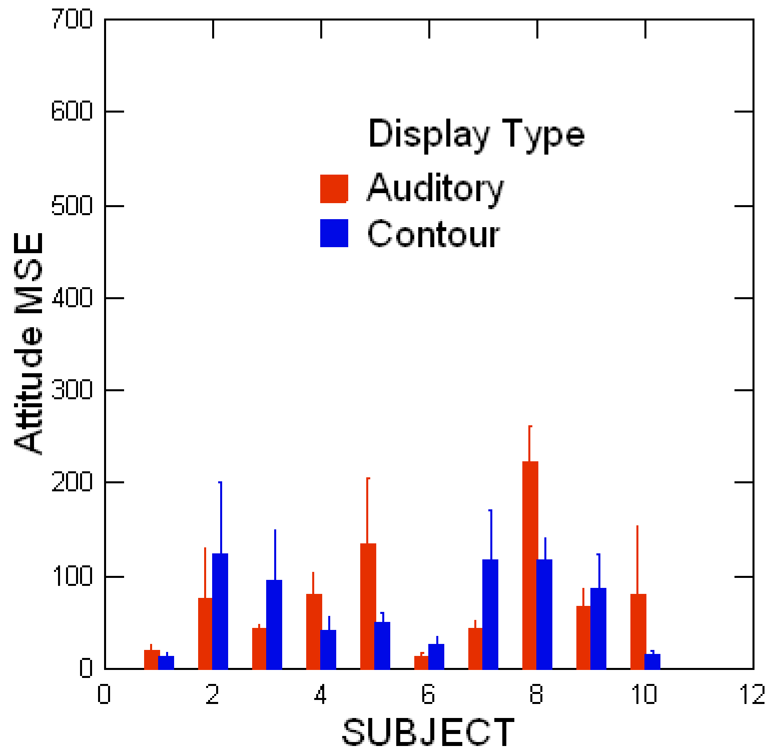


Figure 74. Attitude mean square error by subject for each display condition (avg +/- std err)

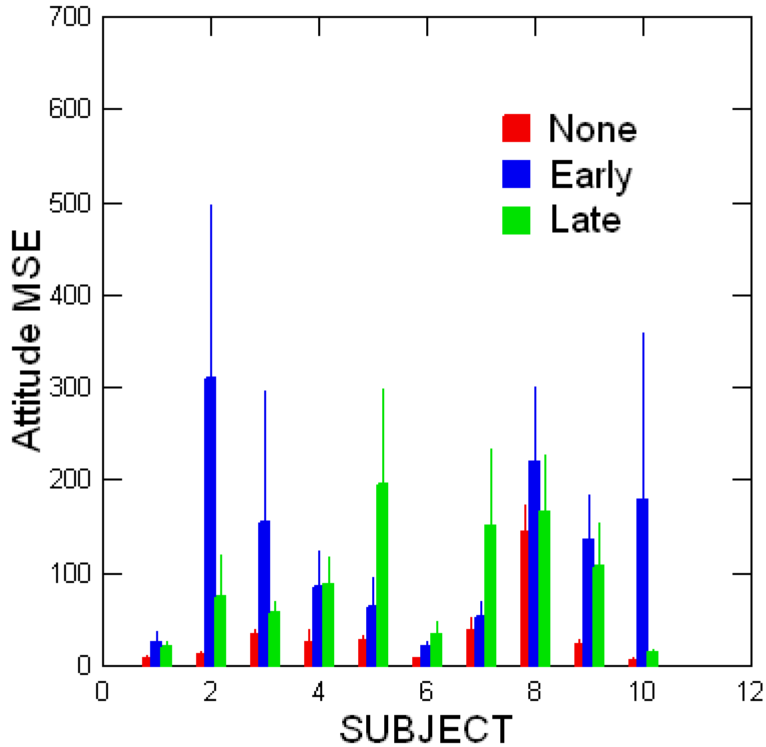


Figure 75. Attitude mean square error by subject for each redesignation condition (avg +/- std err)

Secondary Workload

Secondary workload was measured by the response time to a communications signal as described in Chapter 3. Approximately 10 signals were given to the subject during each trial, and the logarithms of the response times were averaged to determine the response time metric. The logarithms were used in order to normalize the distribution of the errors for regression modeling. Most subjects performed similarly on the side task, with response times of approximately 1 second (Figure 51). It was observed that subject 3 had a different prioritization of tasks, as indicated by a nearly exclusive focus on the primary flight task, and only cursory attention to the side task (which was on the landing area display). Subject 3 did not have any flight or simulator experience, so it is possible that the subject's entire workload capacity was consumed by the primary task. This was not reflected, however, in the Modified Bedford workload ratings given earlier in this chapter. Therefore, the narrow region of focus is a plausible explanation for this difference in response times.

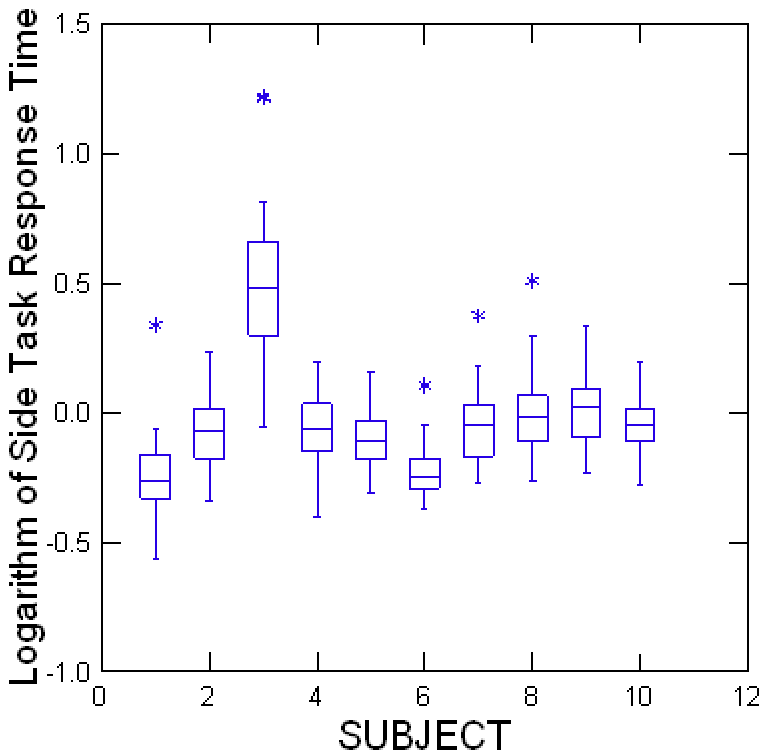


Figure 76. Average log(side task response time) by subject

There was no observable effect of display type (Figure 52). Some subjects showed differences based on control type, but there were no consistent effects seen across all subjects (Figure 53). This indicates that the chosen side task was not sensitive to workload changes based on control mode. Future experiments should implement a more sensitive measure of secondary workload, and this is discussed in further detail in Chapter 5. Response times based on redesignation type are graphed in Figure 54. There is a consistent increase in response time from "none" to "early" to "late" cases. A mixed model hierarchical regression was performed to analyze the significance of the main effects of redesignation type, control mode, and display type. The cross terms of each (including the cross of all three) were also tested, but were determined to not contribute to the model fit. The results are presented below:

Variable	Estimate	Standard Error	Z	p-value
Subject	-0.030	0.060	-0.502	0.616
Auditory Display	0.004	0.008	0.466	0.641
No Redesignation	-0.018	0.011	-1.618	0.106
Early Redesignation	-0.011	0.013	-0.857	0.391
Late Redesignation	0.029	0.013	2.310	0.021
Automatic Control	-0.001	0.008	-0.176	0.860

Table 7. Mixed Model Hierarchical Regression Results for log(side task response time)

The model confirms the lack of an effect based on display type and control mode, and indicates that late redesignations are significantly higher than the no redesignation and early redesignation cases. Therefore, only the high time pressure of the late redesignations had an effect on side task response time.

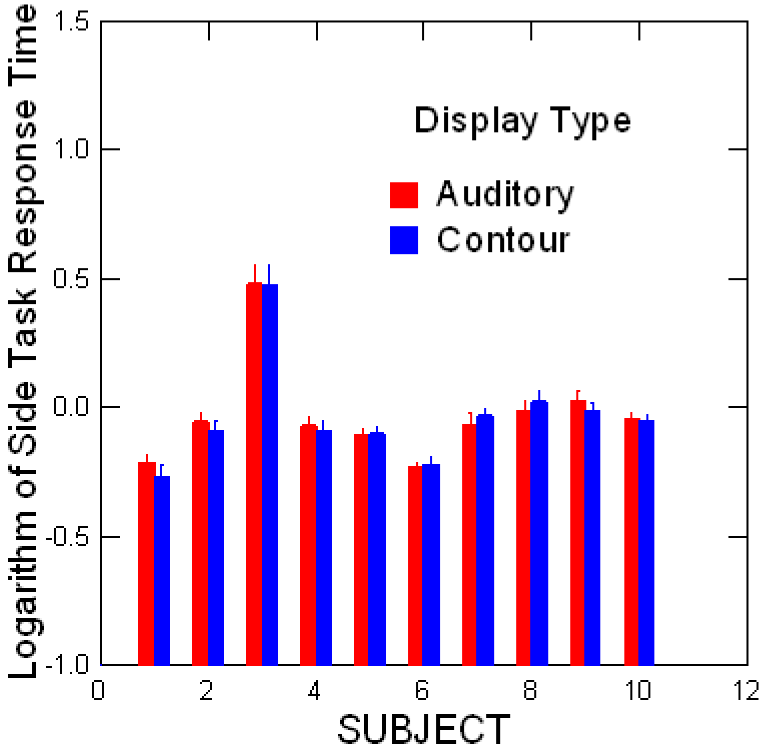


Figure 77. Average log(side task response time) by subject and display type (avg +/- std err)

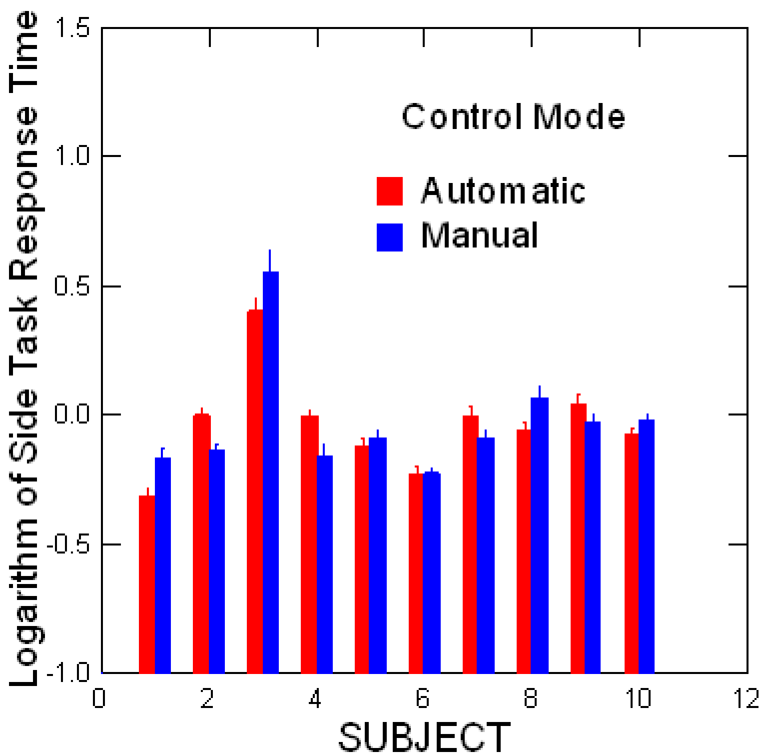


Figure 78. Average log(side task response time) by subject and control mode (avg +/- std err)

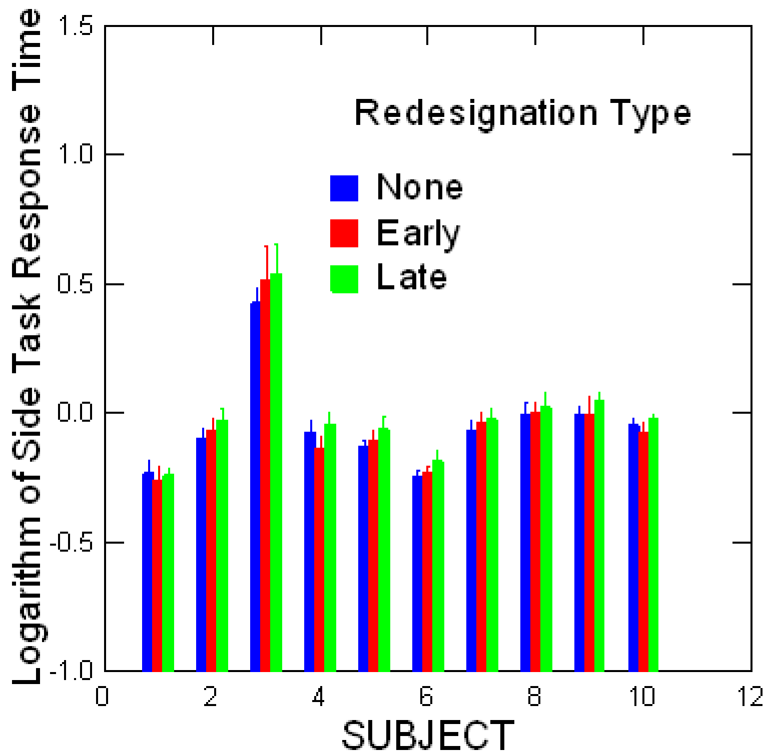


Figure 79. Average log(side task response time) by subject and redesignation type (avg +/- std err)

Fuel Optimal Ratio

Using the fuel contour display, it is sometimes clear that one landing aimpoint is more fuel efficient (optimal) than the other. For the trials that included such a clear fuel optimal point at the time of redesignation, we calculated the ratio of the number of times that the subject selected the fuel optimal point to the total number of applicable trials. To be classified as one of these trials, at the time of redesignation one of the landing points needed to be at least 0.25 inches (at the experimental display resolution) closer to the center of the contours, as measured from the contour edge. Note that this ratio is not related to the fuel at landing, but the number of times that the subject selected the landing point that *should* result in the highest fuel at touchdown. This "fuel optimal" ratio is plotted by subject in Figure 55. The differences between subjects can be explained as the combined effect of redesignation timing, perception of difficulty, and interpretation of goals. There were several maps in which the landing alternative favored by fuel optimality changed close to the time of the redesignation command. For example, the fuel optimal landing target immediately after the redesignation command might be different from the one that is fuel optimal 5 seconds later.

Perceived difficulty also played a role in selection. Several subjects reported that they felt more comfortable redesignating downrange in manual mode to simplify the control task further on. This sometimes resulted in the selection of the less-optimal fuel aimpoint. Subjects also interpreted the goals differently. They were instructed to optimize fuel, and that the landing points were given in order of preference according to the automated system ratings (#1 is preferred). In some cases they chose the automated system-preferred, and in some cases the fuel-optimal alternative. This difficulty is prominent when the #3 automated system alternative happens to be the fuel optimal one. This emphasizes the complex decision-making required in a late-stage redesignation. Further experiments may elucidate the tradeoff of fuel cost and landing point terrain safety (as given by the automated system), and are discussed in Chapter 5.

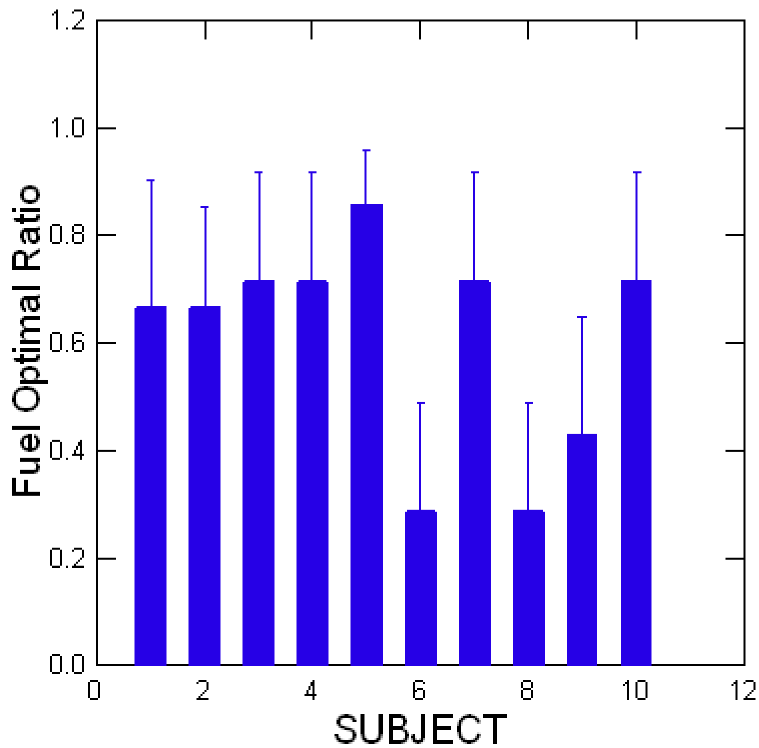


Figure 80. Fuel Optimal Ratio by subject across all applicable conditions (+/- standard error)

The effect of display (contour– auditory, Figure 56) was not significant by Friedman test. The differences among subjects indicate that they used the achievability contour display differently. Some subjects used the display to choose the fuel optimal landing aimpoint, while others did not. Several subjects reported using the achievability contours to improve the assurance that they would reach an alternative chosen by the hazard detection and avoidance system rather than by fuel optimality. In effect, they were not optimizing fuel, but rather their own confidence that they could meet an automated system-preferred landing aimpoint. There were no cases, however, in which subjects chose an aimpoint that was inferior both in fuel consumption and on automated system rating when they had a contour display. By contrast, when they had an auditory display they were less likely to choose the automated system-preferred aimpoint when it had inferior fuel consumption. Further implications of this decision-making process are discussed in Chapter 5.

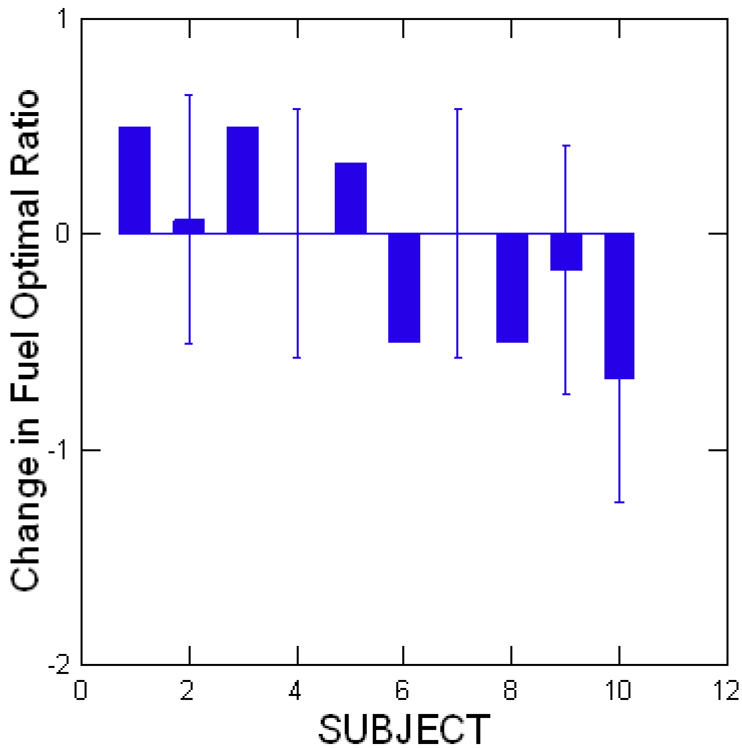


Figure 81. Effect of display on fuel optimal ratio, by subject (+/- standard error)

The effect of control mode (manual – automatic, Figure 57) was not significant by Friedman test. The other decision-making factors (location of alternatives, timing of redesignation) played a more important role in the selection of landing alternate. The effects of landing location and control mode on the fuel optimal ratio are graphed by map in Figure 58 for the applicable conditions (also reference the images of the maps in Appendix III). The redesignation trials on map 6 had a fuel optimal point that was further from the spacecraft location than the less optimal point, and these trials used the auditory display. This suggests that in manual mode, the subjects merely selected the closest landing aimpoint, rather than the fuel optimal one. The selection of the closest alternative in manual mode with the auditory display is supported by the differences in Figure 58. In map 8, the auditory display was used and the fuel optimal alternative was the one closer to the spacecraft location at the time of redesignation. In map 9, the fuel optimal location was further from the current spacecraft location at the time of redesignation, but the subjects had access to the achievability contour display. This suggests that subjects were using the simple judgment of proximity to the spacecraft in the selection of alternates, particularly in the absence of the contour display. It is worth noting that proximity to the spacecraft does not always correspond to the lowest fuel cost, and thus could represent a dangerous pilot decision in an actual lunar landing. Subjects were not instructed specifically to this danger.

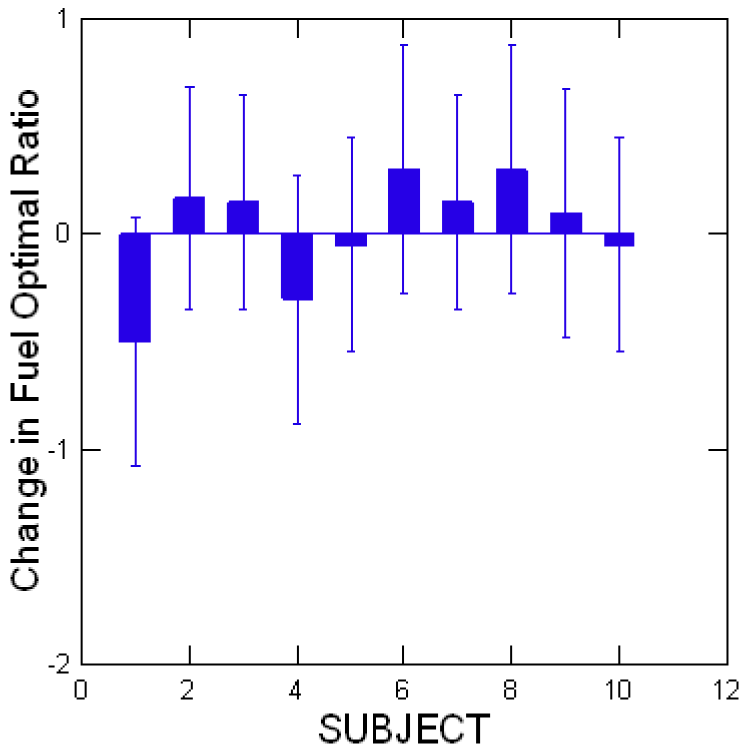


Figure 82. Effect of control mode on fuel optimal ratio, by subject (avg +/- std err)

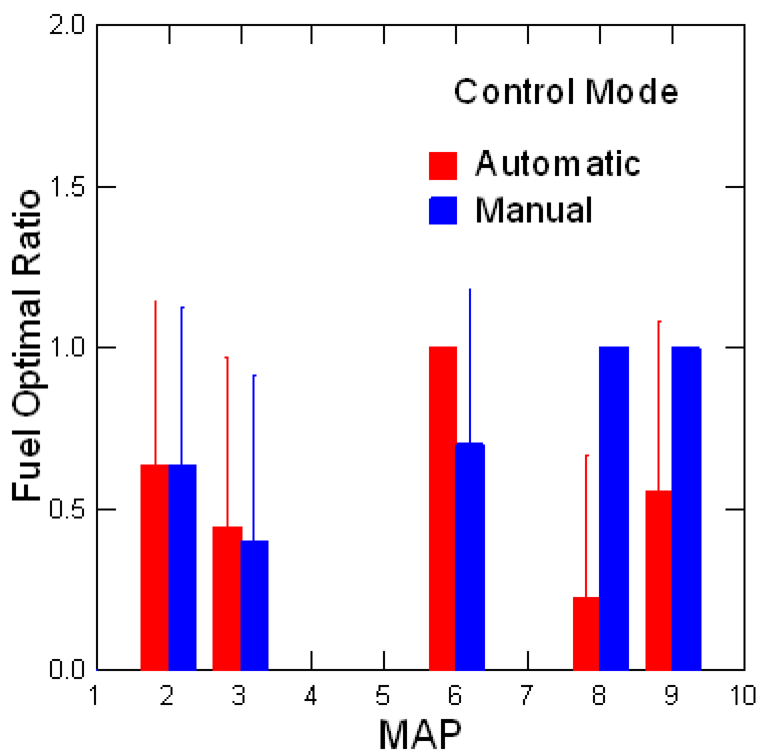


Figure 83. Effect of map and control mode on fuel optimal ratio averaged over subjects (avg +/- std err)

Redesignation effect (late redesignation – early redesignation) on fuel optimal ratio is graphed in Figure 59. For most subjects, that ratio is larger in late redesignations. This follows the logic that under the lower fuel margin conditions of a late redesignation, the subjects must redesignate more conservatively with respect to fuel. However, this effect was (barely) not significant (Friedman test, p = 0.058).

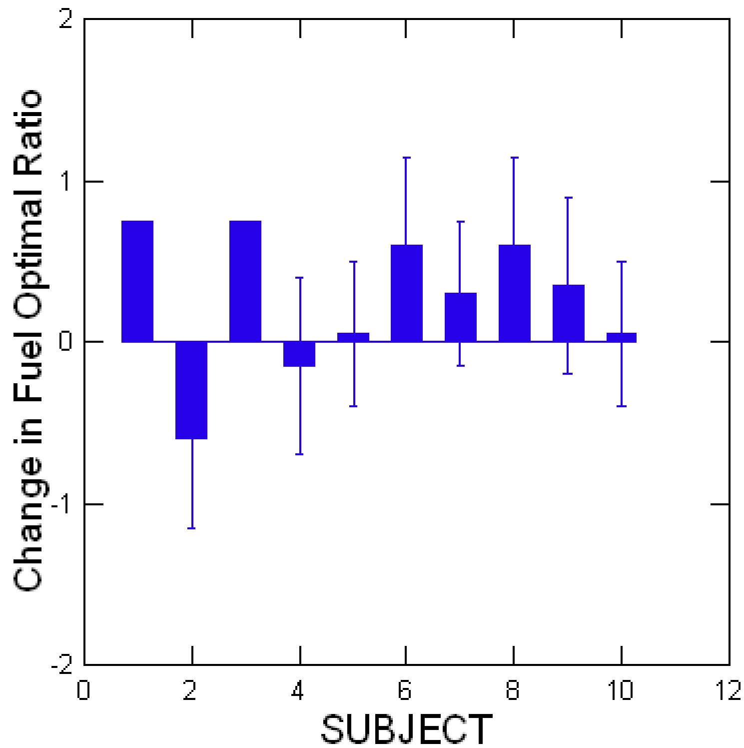


Figure 84. Effect of redesignation type on fuel optimal ratio, by subject (avg +/- std err)

Number of Redesignations

The number of redesignations was the number of times the landing aimpoint was changed, excluding those redesignations that lasted less than 1 second before another redesignation occurred. This exclusion suppressed accidental redesignations and redesignations made to "cycle" through to a different alternate (due to the cyclic selection nature of the experimental landing point designation process). A number of redesignations greater than 1 indicates that the subject changed his/her mind after making the initial redesignation. In most trials, subjects redesignated 1 or 2 times, and every subject redesignated more than once in at least one trial (Figure 60). The extreme outlier in subject 7 was an automatic control mode trial with the auditory display. It represented one of the cases described above where the fuel optimal landing point was changing near the time of the redesignation command.

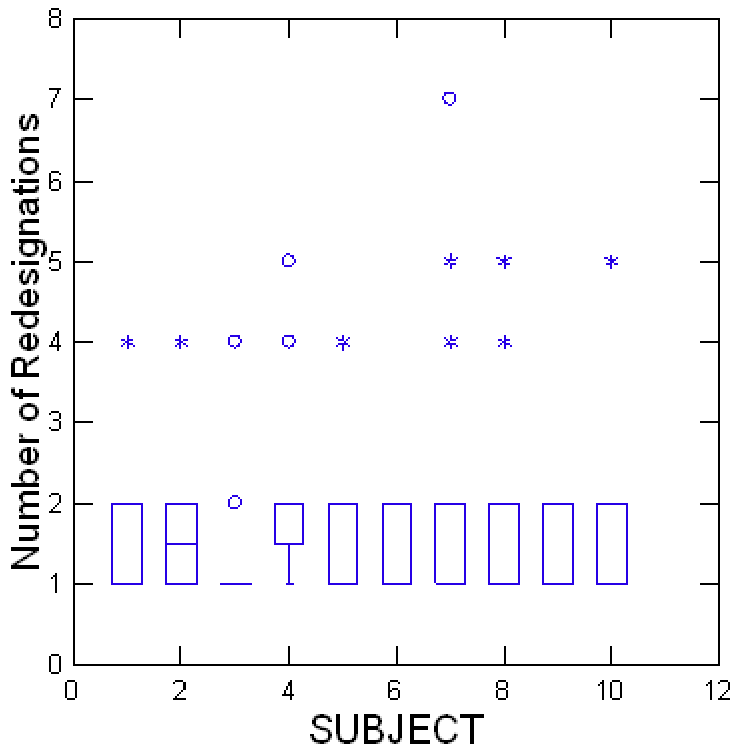


Figure 85. Number of redesignations by subject averaged over all redesignation trials

The locations of landing alternatives—which differs from map to map—can have an effect on the ambiguity in the redesignation options. The number of redesignations, plotted against map type in Figure 61, is roughly the same for all types. Map 6 included some ambiguity (based on fuel usage), but the fuel optimal point was downrange of the initial target. A preferential selection of downrange targets could have reduced the number of times that the subjects changed their mind. In map 5, there was no ambiguity in landing alternate selection, and therefore it is plausible that subjects would select the obvious best alternate and stay with it.

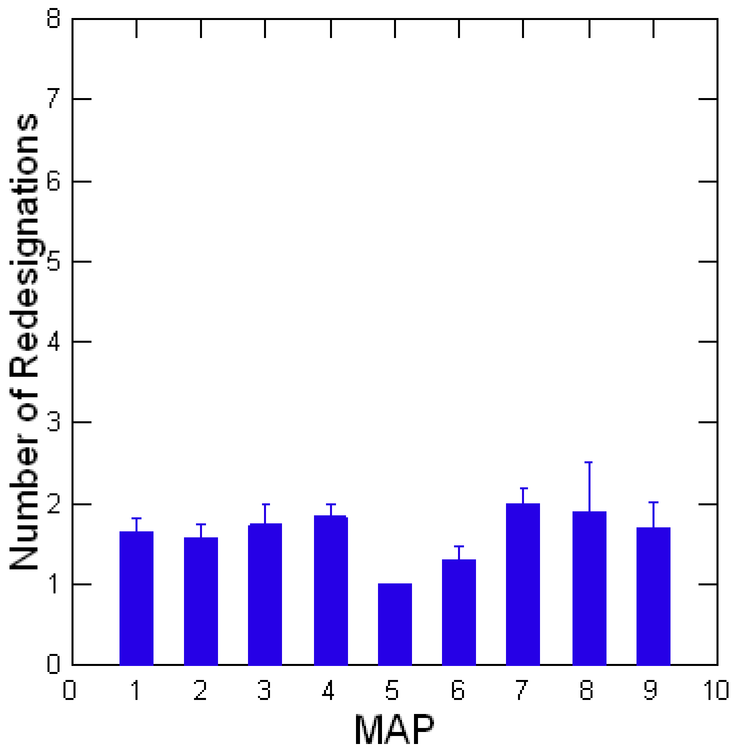


Figure 86. Number of redesignations by map averaged over all redesignation trials (avg +/- std err)

There were no observable differences by display in number of redesignations. A mixed model hierarchical regression was performed with subject as a random effect and main effects of control mode, redesignation type, and display type, and the cross effect of redesignation type and display type. The results of the model are shown below. The main effects were not significant, but the cross effect of redesignation type and display type was significant ($p = 0.028$): there were more redesignations than average with the auditory display and early redesignation. That combination of conditions is particularly conducive to indecision: there is more time and fuel margin for decision-making in an early redesignation case, and the subject does not have immediate knowledge of the relative fuel cost of alternatives because he/she does not have achievability contours.

Variable	Estimate	Standard Error	Z	p-value
Subject	1.620	0.083	19.604	0.000
Automatic Control	-0.022	0.067	-0.330	0.742
Auditory Display	-0.073	0.067	-1.086	0.278
Early Redesignation	0.104	0.067	1.544	0.123
Redesignation x Display	0.147	0.067	2.199	0.028