

Spacecraft Design Considerations for Piloted Reentry and Landing

Abstract

With the end of the Space Shuttle era anticipated in this decade and the requirements for the Crew Exploration Vehicle (CEV) now being defined, an opportune window exists for incorporating 'lessons learned' from relevant aircraft and space flight experience into the early stages of designing the next generation of human spacecraft. This includes addressing not only the technological and overall mission challenges, but also taking into account the comprehensive effects that space flight has on the pilot, all of which must be balanced to ensure the safety of the crew. This manuscript presents a unique and timely overview of a multitude of competing, often unrelated, requirements and constraints governing spacecraft design that must be collectively considered in order to ensure the success of future space exploration missions.

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Introduction

In the novel environment of aircraft flight, where sustained accelerations and degraded visual conditions are frequently encountered, spatial disorientation (SD) and motion sickness can occur as a result of the limitations of the visual, vestibular, and somatosensory systems. Piloting a spacecraft during reentry and landing after a long duration space flight, such as a mission to Mars, could include all of the perception and orientation errors associated with conventional aircraft flight, as well as introduce the added complication of having crewmembers that are adapted to a different gravity environment; a condition that can lead to sensory misinterpretation, hypersensitivity to head movement, reduced visual tracking, and illusions of self-motion. In addition, atmospheric entry may dictate a flight profile with a high deceleration phase coupled with simultaneous multi-axis accelerations, thereby creating other unique sensory problems. Finally, future spacecraft will likely be designed differently than conventional aircraft, creating additional sensory disturbances that could further impair a person's ability to safely pilot a reentry vehicle. Therefore, for any spacecraft that will be piloted during the reentry and landing phases, either as the primary method of control or as a backup to automation, it is essential that sensory disturbances be addressed by design in conjunction with other relevant mission and human constraints. This manuscript describes the aforementioned issues associated with piloted reentry and landing, discusses possible countermeasures, and proposes design considerations for concurrently addressing all of the constraints.

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Spatial Disorientation during Aircraft Flight

In order to maintain postural control, orientation, head stabilization and locomotion, accurate information about the body's attitude, heading and velocity with respect to a fixed frame of reference, such as the gravitational vertical and surface of the Earth, is required. This information is provided by simultaneous inputs from the visual, vestibular, somatosensory and, occasionally, auditory systems. Perception of orientation can therefore be altered if unfamiliar inputs to any one of these systems are presented, which often occurs during flying in situations of poor visibility or when experiencing various levels of acceleration in different directions.

Novel Effects of the Flight Environment

Human sensory systems have evolved to efficiently maintain spatial orientation in the terrestrial environment. As such, they turn out to be poorly suited to the environment of aircraft flight, where novel orientations and sustained angular and linear accelerations frequently occur that are not normally encountered on the ground. Spatial disorientation occurs as a result of the limitations of the sensory systems to accurately provide information during sustained accelerations and degraded visual conditions.

The vestibular system aids in maintaining spatial orientation, balance and posture by sensing head position and acceleration. However, humans typically rely heavily on vision for maintaining spatial orientation on Earth since it is reliable and provides consistent information from most of the three-dimensional environment around us. Good visual cues can override misleading vestibular cues that often occur during flight, allowing a pilot to maintain correct orientation. Therefore, when the quality of visual information is reduced, this "vestibular suppression" does not occur, and the ability to maintain a sense of spatial orientation may also be reduced. An example of this is seen in figure skaters that have learned to eliminate the post-rotatory dizziness and nystagmus (rapid eye movements) normally resulting from the high angular decelerations associated with suddenly stopping their rapid spins on the ice. But even these individuals experience the dizziness and nystagmus expected from their acceleration when deprived of visual cues by eye closure or darkness. As is the case with figure skaters, a pilot's ability to prevent vestibular sensations is also compromised when deprived of visual orientation cues, such as during instrument flight or when looking away from the cockpit instruments.¹ In addition, visual illusions can occur in flight under normal daylight conditions when unexpected visual cues are encountered, as well during other degraded visual conditions such as at night or in bad weather. Visual illusions include the presence of false horizons (night-time roadways),

false surface planes (sloping cloud decks), featureless terrain, haze/fog, and inversion illusions due to unusual lighting conditions; most of which are unique to aviation.² Often under limited visual conditions, vestibular cues are relied upon to assume the role of perceiving body orientation, but may be incorrect and give a misleading perception of spatial orientation. In a study conducted by the U.S. Air Force, insufficient or misleading visual cues were involved in 61% of SD mishaps between 1989 and 1991.³

Vestibular thresholds for detecting motion stimuli are dependent upon a number of variables such as the axis or plane of motion, its frequency spectrum and its duration. Laboratory studies indicate that both transient and sustained motions are unlikely to be detected if the change in angular velocity or the peak linear acceleration is less than certain thresholds. Mulder's constant, which describes this threshold, is approximately 2° per second, and remains fairly constant for stimulus times of about five seconds or less.¹ For sustained motions in flight, if the acceleration experienced is below the threshold detection level, large changes in attitude can occur that the person may be completely unaware of in the absence of supporting visual cues.

Also during a sustained turn, additional perceptual errors arise when the resultant of the acceleration vectors from the turn and from gravity becomes accepted as true vertical, even though the aircraft is no longer aligned with the gravitational vertical. This is due to the fact that the vestibular otoliths cannot distinguish between gravitational force and the inertial reaction force arising from linear acceleration. Examples of this so-called 'somatogravic illusion' are the sensation of a nose-up change in attitude during sustained acceleration in the line of flight on application of increased thrust, and, conversely, the apparent nose-down attitude sensed with deceleration (Fig. 1).

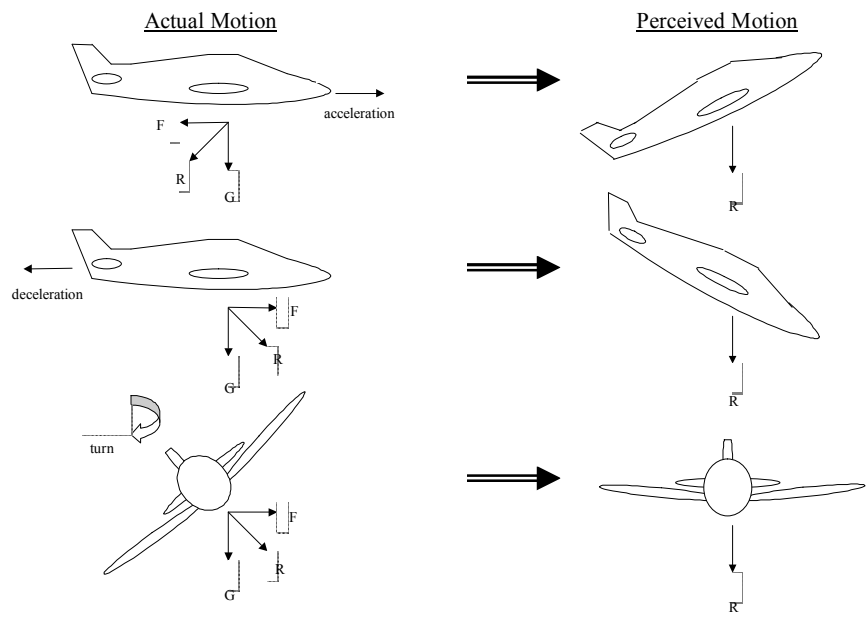


Fig. 1 Illustrated Causes of Somatogravic Illusions

Coriolis stimulation of the vestibular semicircular canals, which sense angular acceleration, occurs whenever an angular movement of the head is made in the presence of rotation about another axis. For example, during steady rotation about the body's vertical axis with the head held vertical, there is no stimulation of the canals and no sensation of rotation. However, as soon as the head is tilted in roll to the left, the sagittal (pitch) canal is brought into the plane of rotation, and the transverse (yaw) canal is taken out of the plane of rotation. As a general rule, a head movement made in one axis (roll) after rotating for some time about an orthogonal axis (yaw) produces an illusory sensation in the third orthogonal axis (pitch).⁴

There are also disorienting sensations associated with stimulation of the otoliths when the head is tilted in flight. During the g-excess effect, where linear acceleration greater than 1g occurs, the otoliths are stimulated in an atypical manner when the head is moved. When moving the head in hypergravity, an otolith signal is generated that corresponds to a greater change in attitude than has actually occurred. The semicircular canals and receptors in the neck signal the angular movement of the head with little error, so there is a mismatch interpreted as a change of attitude of the aircraft in the plane and direction of the head movement.⁵ At higher accelerations, vertigo and sensations of tumbling, as well as an apparent change in attitude, can be evoked by a head movement.

Table 1 Summary of Vestibular Effects and Causal Factors in the Flight Environment

<u>Flight Environment Factors</u>	<u>Vestibular Effects</u>
Novel orientations	Vestibular suppression
Sustained acceleration	“Leans”
Subthreshold (unsensed) motion	Coriolis stimulation
Poor visibility	“Washout”
Visual illusions	Somatogravic illusion
Cabin pressure changes	g-excess effect
	Alternobaric vertigo

Cockpit Design Factors and Spatial Disorientation

There are several cockpit design factors that influence the occurrence of SD. The first tool for maintaining orientation during the complex task of flying is the wide array of information available in the cockpit that enables the pilot to understand the direction and position of the aircraft. This information is conveyed visually from the outside environment via windows and from inside the aircraft via various instruments or displays. Since vision is arguably the most important sense for maintaining orientation, windows providing adequate external Field of View (FOV) of important visual cues should be a key design element. However, as the complexity of aircraft increases, so does the need to rely on additional information provided by the cockpit displays, which can partially replace degraded visual information and provide navigation information, as well as indicate the health and status of the aircraft. The principle display categories are: a) *control* – display aircraft power and attitude, b) *performance* – display the aircraft’s response to control inputs (airspeed, altitude, vertical speed, heading, angle of attack, rate of turn), and c) *navigation* – display information related to geographic location and direction of travel. Even with all of this information available, and sometimes because of it, there are opportunities for SD to occur. Even in visual meteorological conditions (VMC) where the pilot can clearly see the environment through the window, some displays are still relied on to fly safely, thus requiring continual shifting of attention from outside to inside the aircraft. Frequent head movements associated with this continuous scanning, especially during turns or high-g maneuvers, can induce the orientation illusions mentioned previously and also give rise to motion sickness. Research has shown that SD is often caused by transitions between real-world visual cues and displays.^{1,6} With multiple displays providing various pieces of information to the pilot, they should be designed to be simple to interpret, and located together according to function. Grouping related displays together allows for efficient display scanning and minimizes unnecessary head movement. Research has also been conducted into optimizing the

location of various displays within the pilot's field of view. For example, the time needed to perceive roll attitude from a central display was found to be shorter than for roll rate, which was perceived faster from peripheral field displays than from the central display at equal accuracies.⁷ In general, displays should be positioned in the direction of motion, with axes of motion as similar to those of the aircraft itself as possible. As such, a heading indicator that is placed off to one side of the cockpit instead of straight ahead may provide correct information, but since it is located in a position that is not aligned with the vehicle motion, it will require increased head movement to read, as well as more thought and concentration to interpret. Displays should also be large enough to allow for quick and accurate understanding. The small cockpit size of the F-16 required a drastic reduction in display size, resulting in suboptimal line of sight for a rapid recovery from SD.⁸

Besides the displays that tell the pilot about the orientation of the aircraft, there are several controls that facilitate maneuvering. The design of these controls can also play a role in helping maintain spatial orientation. A control should move in a direction similar to that of the resulting aircraft motion in order to be the most intuitive. For example, moving the control stick to the right should also move the aircraft to the right (right roll), and pulling the stick back should tilt the aircraft backwards (upward pitch). This may seem an obvious point, but with today's "fly-by-wire" technology in which control devices are not physically connected to control surfaces, any input in any direction can move any control surface via computer interface. In order to respond in an expected manner, therefore, the location, size, and displacement of controls should also be standardized to a sufficient degree such that flying skills acquired in one type of aircraft can be retained and transferred to other types. Critical switches, levers, and controls must also be safeguarded against inadvertent operation. Especially during emergency conditions, where response time is critical, control of the vehicle must be intuitive.

Aircraft cockpit design has essentially been optimized for safe and effective operation. However, several new devices and displays now being incorporated into the cockpit in order to aid in situational awareness have been found to create their own SD problems. Examples of such devices include: Heads-Up Display (HUD), Helmet-Mounted Display (HMD), and windowless cockpit. Specific performance issues related to each are summarized as follows.

The HUD displays a virtual image of certain flight parameters that appear to float in space through the cockpit window. The HUD SD problem was first identified in U.S. Air Force pilots, 30% of whom reported an increased tendency toward SD when flying HUD-equipped aircraft.⁹ One characteristic of these displays that may

promote SD is that monochromatic lines are often used instead of multicolor patterns, which may not provide adequate information in some cases, such as how the traditional AI indicates the ground and sky with black and blue hemispheres to help the pilot distinguish between upright and inverted flight. A problem that has been noted for over a decade is the inability to detect outside ground and airborne objects while using the HUD. This may be due to excessive clutter, difficulty interpreting HUD symbology, as well as the inward optical and attentional shift of the pilot.¹⁶ Pilots also tend to restrict their head movements and visual scanning to the HUD rather than the rest of the cockpit and outside environment.^{10,11} Related to this is the tendency of pilots to use the HUD's flight-path marker rather than pitch attitude as the primary control symbol, which can lead to inappropriate control inputs for recovery from unusual attitudes. Better HUD technology and symbology and more pilot training may help reduce some HUD-related SD problems.

HMDs were initially introduced into the cockpit to enhance weapon-targeting capabilities, but there is currently an effort to use them for attitude reference displays. HMDs are similar to HUDs, but due to the close proximity of the display, there is a large field-of-view (FOV) limitation that interferes with the view of the cockpit instruments and the outside environment, hence decreasing the pilot's orientation cues. HMDs used in flight are usually of a monocular design, as in the AH-64 Apache helicopter application, providing information to only one eye. This configuration may affect depth perception and the ability to focus. In a survey conducted by Rash & Suggs¹², one out of four pilots reported having some difficulty in purposefully alternating between separate visual inputs to each eye. There are also technical shortcomings with head-tracker systems, which can result in display lag as the head is moved. Table 2 summarizes various cockpit design factors and their influence on SD

Table 2 Cockpit Design and Resultant Influence on SD

<u>Cockpit Elements</u>	<u>Design Factors</u>	<u>Influence on SD</u>
Instruments	Size, location, grouping	Increased head motion, vision & motion not aligned
Windows	Size, location, FOV	Reduced visibility, poor FOV
Controls	Location, direction, intuitiveness	Altered limb feedback & control
HUD	Clutter, symbology	Attentional shift
HMD	Clutter, focal distance	Difficulty focusing, altered depth perception, FOV limitation, display lag

Countermeasures for Spatial Disorientation

It has been demonstrated how cockpit displays provide information about an aircraft's motion and orientation, yet at the same time can also provide disorienting cues. Therefore, some nontraditional cockpit and display technologies are being developed specifically to help counter SD. Examples of these include three-dimensional (3-D) audio, tactile displays, and increased automation (Table 3).

The advantages of using a three-dimensional (3-d) audio device include not only the primary information conveyed in the signal itself, but also relevant directional information, depending on the virtual source of the sound in the headset. Audio inputs of this type may include verbal commands for recovering from an SD incident, as well as a continuous tone indicating a specific direction such as gravitational "up" or "down". Research on multiple processing resources has revealed that the auditory modality can process information in parallel with vision, and therefore should be able to support spatial orientation in an otherwise visually loaded or impaired environment.¹³ However, it should be noted that hearing is inherently less compatible for providing spatial information than vision.¹⁴

Research has been conducted using several different types of tactile display systems in conjunction with traditional displays, in order to provide orientation information. The tactile situation-awareness system (TSAS) developed by the U.S. Navy has shown to be a promising nonvisual tool for avoiding SD by allowing the pilot to sense the aircraft's attitude nonvisually.^{15,16} It does so using arrays of small pneumatically activated tactile stimulators, incorporated into a vest, that are cued by the aircraft's inertial reference system.

It is also believed that the use of cockpit automation will reduce the pilot's workload, thereby allowing more time and concentration for flying the aircraft, and thus reducing the likelihood of SD. SD may also be resolved by temporary use of an autopilot system. In spite of the benefits, cockpit automation also imposes costs, frequently expressed in the form of accidents and incidents attributed to the breakdowns in coordination between the pilot and automated systems.¹⁷ Therefore, if automated systems are to be used, the amount and type of automation must be carefully considered.

Sensory Disturbances during Reentry and Landing

Space Flight Factors That Contribute to Sensory Disturbances

While sensory disturbances such as SD frequently occur in aircraft flight, they are even more likely to

occur upon return from space flight. Descent and landing after a space flight could include all of the perception and orientation errors associated with aircraft flight, as well as crewmembers that are adapted to a different gravity environment, a flight profile with several different acceleration phases, and possibly a spacecraft that is designed differently than a conventional aircraft. If astronauts have piloting responsibilities, this could lead to problems controlling the vehicle, thereby risking the safety of the crew and spacecraft. The prospect of this occurrence challenges scientists and engineers to understand the potential problem and provide methods of reducing this risk.

Adaptation to Weightlessness

Just as a person who is adapted to the 1g environment on Earth is greatly affected upon exposure to weightlessness, so are they conversely impacted upon re-exposure to 1g after a period of adaptation to weightlessness. While many body systems are affected by the transition from 0g back to 1g, the vestibular, visual, and musculoskeletal systems exert the most influence on spatial orientation, as described below.

Vestibular System

Evidence for hypersensitivity of the vestibular system during reentry and landing from space flight, as a result of adaptation to 0g, has been noted during several Space Shuttle flights. Entry loads of ~0.5g are often reported to feel more like 1 or 2g, and after landing, small pitch or roll motions of the head are perceived as being much larger angles and head tilts can be perceived as translations.¹⁸ These vestibular disturbances, also associated with visual performance, could greatly reduce the ability to safely land a piloted vehicle, as errors in acquiring information from instrumentation, performing switch throws, tasks requiring eye/head/hand coordination, attitude control, and visual pursuit can occur as a result.¹⁹

Almost all astronauts experience illusions of self- and surround-motion, both during the microgravity and reentry/landing phases of space flight, with intensity proportional to the length of time on orbit. While individual experiences vary, three types of self/surround motion disturbances are commonly reported: (1) *gain disturbances*, in which perceived self/surround motion seems exaggerated in rate, amplitude, or position after head or body movement; (2) *temporal disturbances*, in which the perception of self- or surround-motion either lags behind the head/body movement, persists after the real physical motion has stopped, or both; and (3) *path disturbances*, in which angular head and body movements elicit perceptions of linear and combined linear and angular self- or

surround-motion. These perceptual disturbances seem to be most intense during atmospheric entry and immediately after wheel-stop, as opposed to in-flight.²⁰

Vision

Vision is also affected during landing, as adaptation of vestibulo-ocular activity to weightlessness is not appropriate to the inertial environment encountered during reentry. Physiologic failure of eye movement function occurs during and immediately following a gravito-inertial transition, such as exposure to microgravity and return to Earth. During these periods, the ability to perform one or more of the following functions may be compromised: (1) hold an image on the retina when the head is stationary, during brief head movements, or during sustained self- or surround-rotation, (2) hold the image of a moving target on the retina, (3) bring objects of interest onto the fovea.¹⁹ During one landing in the late 1990s, the Shuttle encountered a strong lateral gust, which caused the commander to have blurred vision, and contributed to what resulted in the hardest landing to date.[‡]

Muscle and Proprioception

Muscle strength, tactile cues, and proprioception are all also affected by the weightless environment of space and each can indirectly affect sensory perception. Astronauts can lose up to 20% of their muscle mass on short-duration missions, and as much as 50% on long-duration missions, primarily in the postural muscles of the legs and back, if countermeasures aren't used.²¹ Knowledge of limb position, or proprioception, is also diminished with the absence of gravity, causing difficulty in limb motion and pointing tasks. During an eyes-closed task on orbit in which crewmembers were asked to reproduce from memory the different positions of a handle, the accuracy of setting the handle to a given position was significantly lower than with eyes-open, which may have been due to lack of knowledge of limb position as well as target location.²² This effect may also be seen during the first phases of reentry where the effect of gravity is still low, and in later phases where the adaptation to microgravity can lead to inappropriate responses in the presence of a more normal gravity environment. It is apparent that errors of these types would become important in scenarios that require crew input for controlling the spacecraft. With diminished limb strength and proprioception, vehicle controls may not provide the feedback expected during certain maneuvers and phases of flight, and over- and under-correction may occur.

[‡] D. Witwer, Personal communication, NASA Johnson Space Center, April 2003.

Multiple Acceleration Phases

The return to Earth from a long-duration mission, such as from the International Space Station (ISS) or a future planetary mission, entails several phases following LEO or interplanetary flight: atmospheric reentry, descent and final approach, and landing. Each phase has a different acceleration profile: LEO and interplanetary flight could be anywhere from 0g to 1g depending on whether or not artificial gravity is used on the spacecraft; atmospheric entry will likely have g-forces ranging from ~1.2g as experienced on the Shuttle up to the 7g during Apollo missions, and possibly greater for interplanetary missions; parachute opening shock up to 20g for a parachute or parafoil landing system; final approach may have lateral g-forces (swinging) if a parachute or parafoil is used; and landing may require large decelerations or create impact loads up to 40g. Each phase will have a different effect on orientation cues, primarily tactile/proprioceptive and vestibular cues, and will likely be even more pronounced as a result of hypersensitivity and sensory reinterpretation due to 0g adaptation.

Spacecraft Design Factors – A Case Study: ISS Crew Return Vehicle

The originally planned ISS Crew Return Vehicle (CRV), or X-38, was designed to return to Earth with up to seven crewmembers. The CRV design featured a lifting body concept, which derives its lift from the shape of the entire vehicle instead of from the wings alone (Fig. 2). Because of this design, the CRV reentry would have been more similar to the “flying” motion of the Space Shuttle than the ballistic entry of the earlier space capsules. In addition, a steerable parafoil was to be deployed for the final descent and landing phase.

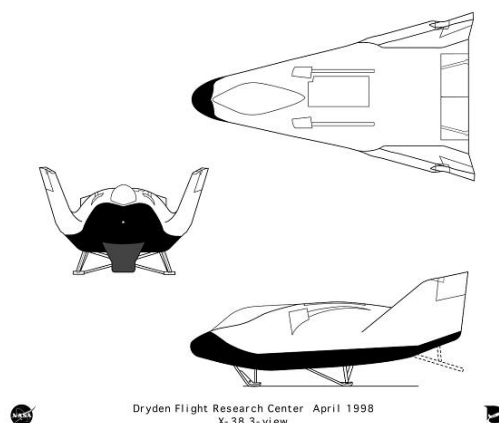


Fig. 2 ISS Crew Return Vehicle (X-38) (Courtesy of NASA)

Some key details of the cockpit include crewmembers lying on their backs with displays mounted on the ceiling, a layout largely driven by limitations of the CRV’s geometry. Where almost every human-operated vehicle

has coupled the direction of travel with the operator's chest axis, this design decouples this familiar relationship, likely creating a conflict between vehicle motion and expected self-motion.

With several different acceleration regimes during reentry and landing, there would be several opportunities for this decoupling arrangement to exert an undesirable effect. While on orbit, the greatest translational acceleration forces would be in the vehicle's +X, direction. In the recumbent position, this would create an 'eyeballs up' acceleration on the crew during departure from the ISS and during all orbit adjust burns. During entry, the vehicle would initially fly at an angle of attack of 40 degrees, and drag deceleration in this attitude would generate an acceleration in the -Z or 'eyeballs in' direction. The angle of attack would eventually be reduced to where the CRV floor is nearly parallel to the horizon as the vehicle assumes conventional aircraft forward flight. Accelerations in this mode would be a near constant 1g. Finally, during parafoil flight, the vehicle would continue the constant 1g level flight deck attitude but lateral accelerations would be sensed by the crew as the vehicle swings under the parafoil during turns. Throughout much of the flight profile, the vehicle would be capable of significant roll, pitch, and yaw performance.²³

Tactile cues that are important for determining orientation are also affected by recumbent positioning. This "seat-of-the-pants" sensation provides information about g_x acceleration through the back, and about g_z acceleration through the gluteal region during upright flight. With a recumbent crewmember, this information would be switched with g_x acceleration now sensed through the gluteal region, and g_z acceleration sensed through the back.

Depending on the design, vehicle controls may be in line with the vehicle motion, but out-of-line with the visual scene motion, or vice versa. This relationship would not be intuitive, or similar to other types of flying. While the CRV was designed to provide a shirt sleeve cabin environment, if the crew is wearing spacesuits, controls must also be implemented such that they are easily maneuvered with gloved hands. The presence of a helmet may reduce visibility and head movement, which must also be taken into account.

Furthermore, recumbent positioning would also reduce forward FOV, likely requiring displays to be mounted on the ceiling as was planned for the CRV, resulting in visual cues that are not in-line with vehicle motion.

It is also possible that in a recumbent position, the direction of acceleration or turning could be misinterpreted by the inner ear. For a crewmember lying on his/her back, a spacecraft roll would stimulate the semicircular canal that normally responds to yaw, so the eyes would be seeing the roll, but viewed on the ceiling display that is not in line with the direction of vehicle motion. Besides SD, this would likely lead to sensory

conflict, which is an underlying cause of motion sickness.

Another design consideration for the CRV was to eliminate windows, thus creating a “windowless” cockpit. The basic assumption for the CRV was that a pilot is not necessary to return the vehicle to Earth, and so a forward-looking window was not a hard-set requirement.

The concept of flying without vehicle windows is accomplished by providing digital video and synthetic imagery to the pilot via a display in the cockpit. NASA has demonstrated that a pilot using a synthetic vision display can safely land a Boeing 737 and also see other aircraft flying in the vicinity as well as any obstacles on the ground, using a 18-in CRT displaying digital video and IR imagery, and radar.²⁴ However, few studies have been performed using windowless cockpits, and there is potential for SD effects. When viewing the outside environment using a single windowless cockpit display, the FOV is severely limited. Griffin & Newman²⁵ investigated 15 experimental conditions for the effects of visual field on motion sickness in cars, and showed that a video-only view of the forward direction resulted in the highest average illness rating, compared to normal and other restricted views. In designs where an external camera can be moved to change the direction of view, SD may occur since the image being viewed in the forward direction is of a visual scene moving in a different direction. If the camera is panned directly to the left, the visual scene and vehicle motion would be 90° out of phase. A sensory conflict may also result since the visual scene has changed, but without a corresponding vestibular input that would normally occur during the head movement that created the change in visual scene. Probst et al.²⁶ exposed 18 seated car passengers to repeated braking maneuvers on a straight motorway in three conditions: 1) eyes open looking forward through window, 2) eyes closed, and 3) a stationary visual field (reading a map). Results showed that the stationary visual field produced the greatest sickness, where the acceleration was in disagreement with the visual information of no movement. This may be extrapolated to the case of visual motion in a direction different than the actual motion, as mentioned above. During tests in NASA’s Remote Cockpit Van (RCV), or “Vomit Van”, which incorporated a windowless cockpit design, test subjects reported disorientation and motion sickness while viewing the external environment on a ceiling mounted display, especially during changes in camera angle, while they remained motionless.[§] In a similar example, it has also been reported that changing the angle of the camera mounted in a

[§] J. Fox, Personal communication, NASA Johnson Space Center, June 2003.

deployed F-16 Maverick IR missile, while at the same time flying the aircraft, was very disorienting.[¶]

With a recumbent crew, SD would be exacerbated not only due to a change in tactile cues, but due to visual cues that would be an additional 90° out of phase with the actual vehicle motion. During reentry, the recumbent position would create an unfamiliar sensation - the view of the outside environment in the direction of travel (forward) would be viewed on the ceiling (upward) instead of the direction of vehicle motion, and if the camera is panned to different angles, there would be an additional discrepancy between the direction of motion and what is being viewed (panning the camera to the left would cause the crewmember to be facing upward, viewing a scene moving right to left, while physically traveling forward). While this would most likely be very disorienting, it could also causevection with a large or close enough display. In one study, subjects on the ground were tested sitting upright and lying supine, and asked to signal the onset ofvection while viewing a series of stripes rotating about their longitudinal axis. Testing in the supine condition resulted in subjects perceiving not only self-motion, but also a graviceptive conflict and the illusory perception of whole body tilt in a direction opposite to stripe rotation, whereas during upright viewing the axis of rotation was aligned with the direction of gravity and thus did not result in a conflict or perception of tilt.²⁷ The results of this study may be applicable to the experience of viewing a display of a camera panned to one side, out-of-line with vehicle motion. Table 4 summarizes the key design elements of the CRV that would most likely affect the crew's spatial orientation.

Table 4 – CRV Design Concerns

<u>Recumbent Seating</u> – decouples crew & vehicle motion
Vestibular System: altered perception of gravity/acceleration
Vision: reduced FOV, not in-line w/ motion
Tactile/Proprioceptive Cues: altered “seat of pants” sensation
<u>Windowless Cockpit</u> – limits quality and field of view
Inherent SD problems
Camera motion increases problems
Recumbent position exacerbates problems

In addition to the unfamiliar sensory inputs from the crew and display location, and possible lack of windows, a returning crew will be adapted to microgravity, as was mentioned previously as creating SD problems in a familiar position, so an unfamiliar position could be even more disorienting (Table 5). Thus, with spacecraft

[¶] S. Horowitz, Personal communication, NASA Johnson Space Center, January 2004.

design, the operator’s physiological condition must be taken into greater account.

Due to the combination of perceptual illusions inherent in flying, vestibular adaptation to a different gravity environment, diminished muscle strength and altered proprioception sense, the many different directions of acceleration, and the possibility of an unconventional cockpit including a reclined seat position with limited visual inputs; attitude, position, and motion perception will almost certainly be affected and could impair an astronaut’s ability to pilot the vehicle. Therefore, countermeasures must be developed specifically for vestibular disturbances during reentry and landing in order to ensure the safety of the space flight crew during a piloted landing.

Table 5 Space Flight Factors that Influence Spatial Disorientation

<u>Space Flight Factor</u>	<u>Influence on SD</u>
Physiological Adaptation	Vestibular - Hypersensitivity to head motion - Self/surround motion disturbances Visual - Reduced object tracking - Difficulty focusing Musculoskeletal & Proprioception - Reduced limb feedback and control
Flight Profile	Several different acceleration phases - Changing and unfamiliar vestibular, tactile cues - Accelerations misinterpreted with adaptation
Spacecraft Design	Crew position, window/instrument location - Altered vestibular, visual, tactile cues

Countermeasures for Sensory Disturbances during Reentry and Landing

Human space flight is a relatively new frontier, and is still largely treated as “flying” in space. This idea often creates the subconscious belief that a spacecraft should be designed much in the same way that an aircraft is designed. However, we are learning that the two modes of transportation have different effects on the human operator, and this needs to be taken into account in the design of the human-machine interfaces. While some types of countermeasures adopted for reducing SD in aircraft may also be useful in spacecraft, space travel is unique and requires unique countermeasures.

Cockpit Design Considerations

Since vision is the most valuable sense for maintaining orientation, the first design consideration should be optimal location of windows and displays in order to provide adequate visual cues that are consistent with vestibular

and tactile cues; and to reduce Coriolis stimulation of the semicircular canals during head movement, which can cause disorientation and motion sickness. Thus, a windowless cockpit, especially with a single display, may not provide sufficient visual input. A cockpit that allows both forward and peripheral views of the horizon would provide the best visual cues for maintaining spatial orientation during piloted landing.

While the effect of seat angle with respect to the acceleration vector has been thoroughly researched regarding its use as a countermeasure to cardiovascular distress and impact forces, its possible effect on SD has been largely overlooked, as was discussed in the ISS CRV Case Study above. Individuals who have been in the RCV have reported getting sick in the fully-reclined position during vehicle motion, with symptoms being reduced as the seat angle was raised.[§] Depending on the location of windows and displays, recumbent seating might also limit visibility. One option to minimize vestibular disturbances during a piloted landing phase is to ensure that the vehicle cockpit provides visual, vestibular, and tactile cues to the pilot that are as “normal” as possible. Minimal vestibular disturbances would likely occur with the crew facing the direction of travel (in a near-upright position for a plane-like design), which is most familiar to pilots, with symptoms increasing as a function of decremting seat tilt. It is possible to maintain the head in a forward-facing position to provide proper vestibular cues, and have the body in a reclined position to counteract cardiovascular and impact problems. However, reclined seating would affect tactile cues, and upright seating would also prevent the perception of self-motion and tilt and the graviceptive conflict discovered in supine testing by Thilo et al.²⁷ that was previously discussed. Since the design of the ISS CRV had the astronauts lying on their backs, with displays on the ceiling in place of windows, which would have most likely contributed to vestibular disturbances during reentry and landing, it appears that the relation of the crew’s position, plus the location of displays and windows (or the lack thereof), to vestibular disturbances is a novel consideration.

During the transition from 0g to 1g and greater, when the Space Shuttle is under automatic control, some commanders and pilots report that moving their heads around intentionally to evoke a sensation of tumbling or dizziness helps to reduce their vestibular symptoms later during the piloted phase of landing.[¶] However, while head movement during reentry causes vestibular problems for most astronauts, the type and degree of these sensations is different for everyone, and can even be incapacitating for some. Additional research is needed before a standardized protocol for head movement during reentry can be developed. Therefore, enabling the pilot to remain upright, facing and viewing the direction of travel during the piloted phase, is currently the best option for reducing vestibular disturbances, and enhancing the safety of the entire crew at one of the most critical times of a space flight.

This is an especially germane point given the current exploration goals and future directions of the U.S. Space Program as outlined by President Bush on January 14, 2004.

Automation vs. Human Control

One design factor for minimizing the negative effects that space flight may have on the crew's ability to pilot a vehicle is to reduce the amount of pilot control needed by increasing automation. Given the likely complexity of a reentry vehicle, some use of automation is certain, especially during descent and landing sequences. Although a fully-automated vehicle would make vestibular disturbances a non-critical issue, it can be argued that the capability must be provided for human override of the vehicle controls during critical landing phases.

The use of automation in aerospace vehicles has already greatly improved the effectiveness of the pilot by performing many time-consuming tasks such as navigation, system-monitoring and fault diagnosis, as well as complex tasks such as those involved in high speed maneuvering and precision flight-path management. Nevertheless, it is valuable to keep humans in the loop because computer-based decision-making cannot match the cognitive ability of the human brain, which can be important during emergencies and critical off nominal tasks. History has shown that the overall contribution of the flight crew increases the probability of mission success because, in addition to being available to respond to hardware failures and unanticipated natural events, a human can overcome many latent errors in hardware and software design if proper attention is paid to the human-machine interface.²⁸ Computers used in automation are necessary when a task requires rapid and accurate computations. Thus, automation should be used during atmospheric entry where heat and g-load damping are critical. However, unlike humans, computers have virtually no inductive or creative capacity, and usually cannot adequately handle unexpected situations such as those that may occur during the descent and landing phase. The importance of human intervention has been evident from the beginning of human space flight. John Glenn manually piloted Friendship 7 during his second and third orbits due to difficulties with the automatic pilot controls, which failed due to apparent clogging of a yaw attitude control jet. Also, if the historic flight of Apollo 11 had an automated moon landing, the crew's safety would have been in doubt. Because of the intervention of the human pilot during landing, a boulder field in the landing zone was avoided and a safer site chosen. While better sensors and navigation tools will be available in the future, other unforeseen obstacles may require real-time human decision-making.

A fully-automated reentry and landing was possible during Mercury, Gemini, and Apollo returns because

avoiding undesirable terrestrial terrain was not necessary due to a water landing. Nor was high accuracy landing required, since a rescue team was deployed to find the capsule wherever it ended up. Similarly, during Soyuz returns, rugged terrain is avoided by landing in the barren landscape of Kazakhstan, and rescue crews are available to rapidly locate and retrieve the capsule. It is interesting to note, however, that a computer error caused the ISS Expedition 6 Soyuz spacecraft to land nearly 300 miles short of the planned landing site, and also caused the crew to endure severe gravitational loads during reentry. It is possible that the capability of human intervention at some point during this time could have allowed for corrections to be made. Also, the Space Shuttle is capable of landing automatically (crew must deploy landing gear), but this has never occurred, as the commander has always taken control of the vehicle at around Mach 1.

Assuming some amount of human vehicle control is used, human constraints must be taken into account accordingly to make sure the operator can achieve adequate monitoring and control. Because it is prudent to design for a worst-case scenario (in the case of the CRV, a medical emergency where crewmembers are unable to pilot the vehicle back to Earth), a vehicle should have the ability to land with full autonomy or with ground control, if necessary. In fact, the Space Shuttle is capable of landing automatically (crew must deploy landing gear), but this has never occurred, as the commander has always taken control of the vehicle at around Mach 1.

If a roundtrip to Mars is to be successful, it is essential to ensure crew safety upon arrival there during the risky phase of landing, and again upon return to Earth. Based on some of the prior experiences described above, these operations may demand human intervention to ensure a safe landing, since landing sites on Mars may be uneven and rocky, there may be visibility limitations with dust storms, and high winds are prevalent. Also, there is no navigation infrastructure on Mars, such as radar and GPS, for spacecraft guidance systems, making human input even more important. The health and safety of the crew upon arrival at Mars are also more critical than on return to Earth, since limited resources will be available to treat injuries.

Artificial Gravity

A related concept that must be considered is the application of artificial gravity achieved through rotation of the spacecraft or a localized onboard centrifuge.^{29,30} Creating a 1g, or partial-g, environment on a long-duration space flight would mitigate most of the negative effects that weightlessness induces on the cardiovascular, musculoskeletal, and vestibular systems; thereby eliminating many of the design measures proposed to counteract

the resulting human constraints. Because of the potential benefits, artificial gravity is an area of research that is gaining a lot of momentum. However, there are still numerous challenges associated with this technology, and a great deal of additional research is required before this can be considered a feasible option. Table 6 summarizes the proposed countermeasures for SD that may occur during reentry and landing.

Table 6 Proposed SD Countermeasures

<u>Cockpit Design</u>
FOV – full (forward and peripheral)
Crew position –head/body facing motion
Instruments/displays – in-line w/ motion
Controls – intuitive, in-line w/ motion
<u>Technology & Training</u>
Automation (phase- & task-dependent)
Pre-landing adaptation training
Artificial gravity

Current Research

With increased manual pilot control comes a greater need for ensuring a familiar sensory environment. This concern influences the angle at which the pilot is positioned with respect to the velocity vector, the location of controls and displays to minimize head movements, and may also require the use of windows or high-fidelity synthetic displays for natural visual input. Test subjects driving the RCV, which served as a CRV landing simulator to test the windowless cockpit concept, have reported feeling nauseous during trial runs, which could be a function of the recumbent seating arrangement as well as the design of the visual environment displays. In early designs, changing the view on the single display was accomplished by moving the externally-mounted camera with a hand-controller. This technique may have caused a sensory conflict since there was no corresponding head motion with the moving visual scene. An HMD system was later developed for the RCV, where head motion of the subject coordinated the activation of several cameras pointed in all directions to provide a 360-degree view outside the vehicle.[#] However, this technology incurs the same vision-limiting and head tracker limitations as other HMD applications. Windows allowing a view in the direction of travel, as well as peripheral views, would provide the most natural visual inputs to the pilot, but high-quality video may also be effective if properly designed. Instead of a single display, an effective design should include an array of displays, creating a full-FOV virtual cockpit window.

[#] J. Fox, Personal communication, NASA Johnson Space Center, February 2004.

This would also allow the pilot to move his/her head instead of the camera in order to change the view, thus negating the potential conflict between vision and vestibular system. NASA's Human Flight Vehicle Development Office at the Johnson Space Center is currently developing a similar system for the RCV, using an arrangement of five displays to create a virtual window, with crewmembers upright.[#] The current development of the RCV utilizes synthetic imagery in conjunction with real-time video in order to provide an all-weather, day/night situation awareness display. This technology is ideal for augmenting a crewmember's situational awareness in tasks such as helping to select a landing site or manually flying the vehicle during the parafoil flight phase. The RCV group also plans to measure subject motion sickness symptoms as a part of their future testing to determine whether this design is effective in reducing these undesirable effects.

While a full FOV and an upright crew position are likely the most simple, straightforward and beneficial considerations for minimizing the concern of detrimental effects of vestibular disturbances during reentry and landing, it is important nevertheless to determine the overall feasibility of this solution by taking into account other human constraints and mission constraints. Historically, a recumbent position has been used as a countermeasure for cardiovascular and musculoskeletal problems upon return to 1g, and so crew positioning must be better understood before adopting it as a design solution for vestibular concerns. Decision factors regarding how the crew will be positioned start from the basic mission constraints, including how the vehicle enters the atmosphere and the vehicle shape.

Spacecraft Design Guidelines

Mission Constraints and Design Considerations

The design process begins by identifying the mission statement and requirements. For a spacecraft, the first requirements are usually defined in terms of the desired orbital characteristics (inclination, altitude, etc.) and the payload to be delivered. Constraints to the spacecraft shape, size, and weight are then imposed on the design, and arise mostly due to the capabilities of the booster system to be used. From the point of view of launch capability, the ideal spacecraft should be as small, compact, and light as possible, which in essence requires a low lift-to-drag ratio (L/D). For the near-term future of most human space flights, orbital characteristics can be broadly categorized as being either Low Earth Orbit (LEO) or planetary missions. LEO missions may also be subcategorized by their duration, with times varying from days to months. Different mission types will affect the type of vehicle needed and

the physiological condition of the crewmembers during the flight and upon return. In addition to booster system launch constraints, other dynamic phases of the mission, such as during entry and landing, necessitate other unique (and possibly competing) vehicle design requirements.

Atmospheric Entry

As human missions extend to further exploration of space beyond LEO, reentry velocities may increase, ranging from orbital speeds of 25,000 ft/s through lunar returns of 36,000 ft/s to planetary mission returns from 45,000 up to 70,000 ft/s³¹, depending in part on the type of interplanetary trajectory. In order to safely land, the spacecraft must reduce these velocities before or while entering a planet's atmosphere and must also enter the atmosphere within a strict reentry corridor. If the reentry angle is too shallow, the spacecraft will skip or bounce off the atmosphere and out into space. Conversely, if the approach angle is too steep, the heat shield will not survive the extreme heating rates, nor will the crew or spacecraft likely survive the high deceleration *g*-forces.

A spacecraft can reduce its velocity upon arrival at a planet using either propulsive or aeroassist maneuvers. As the name implies, propulsive maneuvers require propellant, which can add considerable mass to a spacecraft. Aeroassist maneuvers encompass various ways in which a spacecraft can make use of aerodynamic forces to reduce its velocity or change its orbit for atmospheric entry, with minimal or no use of propellant. Aeroassist technologies now in use or in development include direct entry, or aerocapture, aerobraking, and aerogravity assist followed by aeroentry.

Direct entry occurs when a spacecraft enters the atmosphere without course adjustment from a high-speed hyperbolic orbit. Aerocapture involves using a planet's atmosphere to decelerate from a hyperbolic approach orbit to an elliptical parking orbit, without the use of onboard propulsion. Aerobraking uses onboard fuel to capture a spacecraft into orbit but, then, utilizes drag from a planet's atmosphere to slow down and place a spacecraft into its final orbit. Aerogravity assist combines the use of a planet's atmosphere, gravity and onboard vehicle propulsion to modify a spacecraft's orbit. The technique is similar to a gravity assist maneuver where a spacecraft flies near a planet and uses the planet's gravitational force to alter the spacecraft's trajectory, but with aerogravity assist, the vehicle flies even closer to the planet, using the atmosphere and gravitational force to slow down. This use of gravity and aerodynamics can help the spacecraft turn more sharply around the planet than with gravity alone, and has significant potential to reduce interplanetary trip times. Aeroentry then transfers the spacecraft from either a

hyperbolic or elliptical approach orbit to the planet's surface, which is how the Shuttle enters the Earth's atmosphere at the end of each flight.

With atmospheric entry there are three, often competing, requirements to consider: heating, deceleration, and accuracy. The type of atmospheric entry and spacecraft design selected will determine the level of influence each of these factors exerts. These requirements also depend on the destination, since, for example, the Martian atmosphere has less than 1% of Earth's surface pressure and about 10% of its density, but also drops off much more gradually with increasing altitude.

The maximum deceleration during direct entry is dependent upon the vehicle's path angle, initial velocity, and atmospheric characteristics. Rather than reenter from an established low Earth orbit like the Space Shuttle does, the Apollo lunar mission flight profile called for a direct reentry that significantly reduced the allowable flight path error margins compared with a typical orbital reentry profile (2° vs. about 8°) and increased the spacecraft's velocity at entry interface by nearly 50% - approximately 36,300 ft/s for direct reentry vs. 25,800 ft/s for an orbital reentry. Flight corridor depths, which allow reentry in a single pass, decrease rapidly as the reentry speed increases if the maximum deceleration is limited. Average maximum deceleration levels for the Apollo lunar missions (6.63g) were also about twice as high as Earth orbital missions Apollo 7 and 9 (3.34g) due to the direct entry method.³² A direct entry from a hyperbolic orbit allows only limited access to surface landing sites, which may be problematic if landing at or near previously positioned resources is required. For a Mars mission, the more gradual density variation in the Martian atmosphere would allow for a lower peak deceleration during direct entry than would be experienced on return to Earth, but if not sufficiently reduced beforehand the entry velocity and angle may cause decelerations too high for human occupants.

Any maneuver that can be implemented to lower entry speed and increase the entry corridor, which occurs when first entering a parking orbit before atmospheric entry, will reduce g-loads and allow for better range and cross-range, depending on the vehicle capabilities. The fuel efficient method of aerocapture could also substantially reduce the mass of an interplanetary spacecraft, allowing for smaller and less expensive launch vehicles or increasing the payload capacity on same size vehicles. However, in order to conduct this maneuver, adequate drag is required to decelerate and therefore adequate protection from the heating environment is also required. Fortunately, this can be accomplished in several ways, including use of a rigid aeroshell like that used during the entry and descent of the Mars Pathfinder in 1997.

Aerobraking can take several months to perform, as in the case of the Mars Global Surveyor launched in November of 1996, which made a series of aerobraking maneuvers over a nine-month period to gradually reduce its altitude and achieve its intended orbit. However, faster, high-energy aerobraking maneuvers can also be performed with the addition of a heatshield.

Because a vehicle using aerogravity assist flies deeper into the atmosphere, it would need to be long and thin, more like a "flying wing" than a capsule, to minimize drag on the spacecraft and provide better maneuvering capability. Thus, a high-performance thermal protection system would be needed to accommodate the high heating conditions of the vehicle's sharp leading edge.

Each method of slowing the spacecraft has specific risks and benefits, which need to be considered with other vehicle and crew constraints (Table 7). The most likely scenario for a Mars mission would include the use of aerocapture or aerobraking into an elliptical orbit, followed by aeroentry of a separate landing vehicle. Aerogravity assist is likely unfeasible mainly due to reduced volumetric efficiency and increased heating, while direct entry is not favorable due to high stress on the vehicle and crew, and low accuracy.

Table 7 Atmospheric Entry Options and Considerations

<u>Atmospheric Entry Options</u>	<u>Considerations</u>
Propulsive	Heating
Aeroassist	Deceleration
<ul style="list-style-type: none"> • Direct entry • Aeroentry + <ul style="list-style-type: none"> - aerobrake - aerocapture - aerogravity assist 	Accuracy

Spacecraft Shape

In addition to, and in conjunction with, the type of atmospheric entry selected, spacecraft shape will determine the levels of deceleration, heating, and accuracy. The general categories that describe human spacecraft entry vehicles (Fig. 3) are, in order of increasing L/D: 1) ballistic (Mercury), 2) lifting-ballistic (Gemini, Apollo), 3) lifting body (X-38), 4) winged (Shuttle), and 5) high-fineness lifting body (X-43). A ballistic spacecraft represents a nearly optimum shape in terms of volumetric efficiency. Lifting bodies have good volumetric efficiency and develop sufficient subsonic lift to allow horizontal landing. As the spacecraft shape approaches the higher L/D's, its fineness increases, necessitating an increase in structural weight due to its departure from the simple, nearly spherical pressure vessel of the ballistic vehicle.³¹



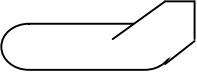


Vehicle Category	Vehicle
Ballistic (Mercury)	
Lifting Ballistic (Gemini, Apollo)	
Lifting Body (ISS CRV)	
Winged (Space Shuttle)	
High-Finesness Lifting Body (X-43)	

Fig. 3 Reentry vehicle shapes

Use of aerodynamic lift can also result in a three-to-five-fold increase in corridor depth over that available to a ballistic vehicle for the same deceleration limits, as well as increase maneuverability in the atmosphere.³³ L/D provides a measure of a vehicle's maneuverability and also gives a good indication of what kinds of g -loads and heating loads it will experience during entry. A vehicle with a low L/D will experience high g -loads and high peak heating. As the vehicle configuration increases in L/D there is an associated increase in weight of the structure and heat-protection system. This is due in part to the fact that as the volumetric efficiency decreases, as it does with increasing L/D , there is more surface area to protect from heating for a vehicle of constant volume. A vehicle with a high L/D can maintain greater vertical and horizontal control to minimize entry deceleration, improve cross-range for landing site flexibility, and decrease peak heating, but because the amount of time in the atmosphere may be longer, the total heat load may be high. Also, vehicles with high L/D usually have sharp leading edges that are more susceptible to heat than blunter shapes. In order to reduce heating and improve cross-range capability, a vehicle with high L/D such as the Space Shuttle must constantly keep adjusting its control surfaces at super/hypersonic speeds, carefully balancing control, range, and heating. Thus, a failure of the guidance or control system could render the vehicle uncontrollable, causing it to diverge a great distance off course, and, without the ability to

properly maintain heat and reentry g-loads, could lead to loss of the vehicle. By contrast, low L/D capsules tend to naturally stabilize themselves bottom-down, keeping their main heat shields downwards into the increasingly dense atmosphere. The structures often associated with high L/D, such as wings, tails, elevators, ailerons, etc., all have multiple component failure modes, whereas a capsule is safer in its simplicity.

Overall, high L/D vehicles have inherent advantages for reentry and landing, but are complex; low L/D vehicles are simple, safe, and efficient, but are not as maneuverable, which is important for the descent and landing phase. Low L/D is also ideal for the constraints of the launch booster system.

The entry corridor's width dictates the flight system's guidance, navigation, and control requirements. For Earth-return missions, the infrastructure for ground-based navigation may reduce requirements on the spacecraft's navigation system. However, for a Mars-approach mission with little or no ground navigation infrastructure, the aerocapture flight corridor's width dictates steering requirements for the vehicle's control system. These navigation limitations may also dictate the need for a human pilot during the terminal landing phase, both for accurate landing and obstacle avoidance. With other parameters remaining constant, changing the angle of attack affects a vehicle's ballistic coefficient and L/D directly and, therefore, immediately affects in-flight performance. Hypersonic Newtonian theory shows that maximum L/D and maximum drag occur at different vehicle attitudes. Therefore, a large angle of attack near $C_{d_{max}}$ (maximum coefficient of drag) in the early, high-speed phase of entry will minimize peak heat rates, whereas a lower angle of attack near L/D_{max} will maximize range and cross-range in the later, lower-speed phase.³⁴ With this type of reentry profile, the initial phase (high speed and angle of attack) would likely require automation, and the final phase (lower speed and angle of attack) would provide better visibility and would be more manageable for a pilot.

Descent and Landing

Descent and landing typically refers to the flight phase that occurs after atmospheric entry, which is designed to reduce the horizontal and vertical velocities to desired values for surface touchdown. Depending on the destination and spacecraft design, this phase may include the use of parachutes/parafoils, powered flight, gliding flight, or some combination of these technologies. In cases where an existing atmosphere permits, a parachute can provide additional deceleration after the aeroentry phase, allowing the spacecraft to further reduce propellant mass. Both the Apollo and Russian Soyuz capsules use(d) parachutes to get terminal velocities of about 9 m/s and 7 m/s,

respectively.³⁴ During the final, unpowered descent, Apollo attenuated touchdown shock by using a water landing, and Soyuz does so by firing a small solid-motor thruster just before touching down on land. The thin atmosphere of Mars does not, in general, allow parachutes alone to sufficiently slow a spacecraft for surface landing. A powered braking and terminal landing phase are necessary for a controlled soft landing. The airless Moon requires an all-propulsive descent and landing phase.

Landing Accuracy

The ability to land at a predetermined location may be important not only for a Mars mission, but for a return to Earth after a long-duration mission. At Mars, it may be critical that a crewed vehicle land nearby pre-positioned resources or an existing outpost. Landing too far away could be catastrophic. Upon return to Earth after a long period in space, the crew may be in poor condition, requiring swift medical attention that would require landing near certain facilities. While the ability to accurately land a spacecraft within a given area is dependent on the type of reentry, it is ultimately also a function of the vehicle's ability to maneuver through the atmosphere to the desired location. With this reasoning in mind, it would seem apparent that vehicles with high L/D are superior to other designs such as the semiballistic Apollo capsules. However, the addition of steerable parachutes, parafoils, or paragliders would allow capsules to avoid obstacles and achieve accurate landing point control, given adequate landing opportunities. The original landing system proposed for the Gemini spacecraft included a paraglider in order to land on a small pre-selected landing site, but despite several successful tests, the idea was abandoned due to cost overruns.³⁵ For Earth return, global positioning system (GPS) guidance would further enhance landing accuracy. Furthermore, historical data indicates that even without the benefit of steerable parachutes and GPS, relatively accurate landings can be achieved, as can be seen with the Apollo program (Table 8).

Table 8 Apollo landing accuracy³⁶

<u>Mission</u>	<u>Distance from Target (miles)</u>
Apollo 7	1.9
Apollo 8	1.4
Apollo 9	2.7
Apollo 10	1.3
Apollo 11	1.7
Apollo 12	2.0
Apollo 13	1.0
Apollo 14	0.6
Apollo 15	1.0
Apollo 16	3.0
Apollo 17	1.0

Impact Attenuation

landing method

The decision to use powered or unpowered means for landing depends on several factors. First of all, in order to utilize a winged or lifting body spacecraft design, or use unpowered devices such as a parachute or parafoil with a capsule, the atmosphere must be sufficient to sustain gliding flight. Thus, landing on the airless Moon requires a propulsive landing phase. Powered flight also requires propellant, which takes up valuable mass and weight on a spacecraft, both always at a premium on space flights.

All flights of the Mercury, Gemini, and Apollo programs successfully utilized parachutes to reduce terminal velocities upon return to Earth. The X-38 lifting body that was intended to return astronauts from the ISS used a parafoil for final descent and landing. The steerable parafoil allowed for more accurate landing site selection than Apollo or Soyuz, as well as slower vertical landing speeds for a touchdown on land. Where Apollo capsules landed within an average of 1.6 miles of the designated landing point, it was believed that, with good parafoil guidance and free-flight guidance, the X-38's landing footprint could be around +/- 980 feet down-track and +/- 330 feet cross-track.** The primary advantages of a conventional parachute are traditionally considered to be high reliability and low complexity, but as a result of more recent extensive testing and development, parafoils are now comparable in these regards. In addition, three advantages are identified for lifting parafoils over conventional parachutes: 1) being able to reduce the dispersions associated with the deorbit and reentry trajectories by using its maneuverability to glide to a predetermined point, 2) having the capability of being manually controlled to minimize

** A. Strahan, Personal communication, NASA Johnson Space Center, February 2004.

landing area impact dispersions and, 3) by flaring, to reduce the vehicle impact shock at touchdown.³⁷ A parafoil can also correct for wind by allowing control of crab angle and orientation, unlike a round parachute. While the Mars atmosphere has much lower density and pressure than Earth, it should still provide enough dynamic pressure for a parafoil spacecraft to perform aerodynamic maneuvers during entry and gliding flight. In order to provide a more natural position with respect to the direction of travel and allow for better pilot control with a parafoil, the flight crew should be seated upright with an appropriate FOV. If a capsule design were used, however, this would mean an upright position being maintained throughout the reentry phase, which could have detrimental effects on the cardiovascular system. Therefore, if a capsule is used with the crew sitting in the traditional recumbent position, it should be tilted on its side when the parafoil is fully-deployed such that the crew ends up sitting upright, similar to the original Gemini-paraglider design. Thus, a typical landing phase for a human mission to Mars might entail an aeroentry followed by a parafoil glide and, if necessary, powered final retro-braking (similar to Soyuz) to ensure a soft landing.

landing on water vs. land

During the early NASA space program, water was selected for landing primarily because it provides an excellent means of impact attenuation, but also for simplicity, since there is no need for terminal landing maneuvers with a capsule using a parachute, and for safety, since the landing site was far from populated areas. Since astronauts were not in space for long periods of time and returned basically healthy, immediate recovery was not required and they were retrieved from their ocean landing site within a matter of hours. However, there are several other factors to consider with a water landing. First of all, the spacecraft must be able to float, which may add to design weight and complexity, and therefore, cost. Even with this capability there is a risk to the spacecraft and crew, as was seen after the splashdown of the Mercury Liberty Bell 7 in which the hatch was prematurely blown, leading to the loss of the capsule and nearly to the drowning of astronaut Gus Grissom. Seawater may also be corrosive to the spacecraft materials, which is an issue for reusable vehicles. Helicopters are required to extract the crew from the ocean, as well as carry the spacecraft to a ship or nearby land. Depending on the weather and sea state, the crew and vehicle may be subjected to wave motion which may cause motion sickness, and also make helicopter retrieval more difficult, putting both the astronauts and rescue personnel at risk. Since sea retrievals entail these inherent risks, a land landing assisted by GPS would be safer in terms of quickly locating and safely retrieving

the crew. With a land landing, most of the concerns of a water landing are eliminated, although impact attenuation becomes more challenging. As discussed above, however, this can be accomplished in other ways such as the use of parafoils, retrorockets, or various shock absorbers. Populated areas can also be avoided with better landing accuracy. Finally, a land landing is the only option upon arrival at the Moon or Mars. For landing on Earth, the same concept for a Mars landing could be used, except that a parafoil flare and skid landing could replace a retrorocket. Table 9 summarizes the options and considerations for the descent and landing phase of a piloted space flight.

Table 9 Descent and Landing Options and Considerations

<u>Design Options</u>
Parachute, Parafoil, Powered flight, Gliding flight, Combination
<u>Considerations</u>
Landing accuracy, Impact attenuation, Water vs. land, Crew physiological condition, Atmospheric density

As a result of the various mission constraints discussed, one feasible design option for a reentry and landing vehicle includes a spacecraft with low L/D, such as a capsule, in order to achieve a safe and efficient atmospheric entry, with the addition of a parafoil landing system to enable better landing accuracy and impact attenuation. This concept would also allow an upright crew seating position for optimal vestibular and visual inputs during the critical final phases of landing (Fig. 4). However, this concept does not address other physiological affects, such as cardiovascular distress and landing impact.

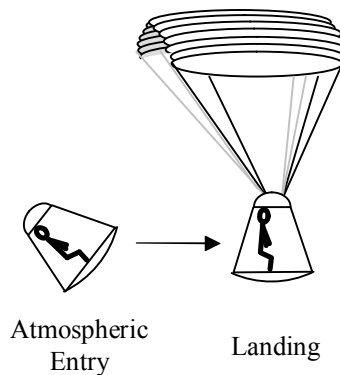


Fig. 4 – Design for Mission and Vestibular Constraints

Human Constraints and Design Considerations

To date, no established standard has been developed to evaluate the acceptability of the pressurized crew compartment volume of a spacecraft. Vehicles are designed to minimize structure, weight, and volume, to fit designated launch vehicle capacities, and to withstand the stresses of launch and landing, largely leaving the pressurized habitable volume available to be an artifact of what remains after all other system components have been installed. Historically, human factors have usually been the first compromise incurred during the spacecraft design, and often not addressed until late in the process.³⁸ There are several physiological concerns that arise over the duration of a space flight, including cardiovascular deconditioning, musculoskeletal atrophy, and radiation sickness to name a few. The focus of this final discussion addresses the more risky phases of flight that occur during reentry and landing. There are currently two primary concerns for the human body during reentry and landing from space flight: 1) cardiovascular distress, including g-induced loss of consciousness (G-LOC), with related visual symptoms and orthostatic intolerance and 2) physical trauma due to landing impact.²¹ These concerns must be taken into account when designing a spacecraft to be safe for the human occupants, especially those crewmembers who may be controlling the vehicle. However, the different effects may be countered in opposing ways, and so compromises must be made.

Once the specific problems have been identified, then design options can be considered for mitigating the detrimental effects on both the vehicle and the astronaut. While this discussion is focused on the reentry and landing phases of a mission, each phase must be considered in order to fully understand the impact of g-transitions and adaptation on the human body. For example, during interplanetary flight between Earth and Mars that may last as long as six months, or even during shorter duration missions, astronauts may experience considerable physiological changes in many of their body systems that may not only affect their performance during the 0g portion of the flight, but may also predispose them to problems occurring during the g-transition upon arrival at Mars or return to Earth.

Cardiovascular Distress

Space flight can create significant changes to the cardiovascular system, starting on the launch pad and continuing on orbit, but are usually of most concern during landing when astronauts are reintroduced to gravity and acceleration. Upon encountering gravity, the body's fluid is now pulled downward, but with reduced blood volume and diminished cardiovascular capacity, hypotension can occur, which is the primary cause for G-LOC and related

visual problems. Due to the reduction in blood pressure, and therefore blood flow to the head, G-LOC can become catastrophic in flight. While it has not been an issue for space flight to this point, the potential for G-LOC should still be considered, especially if returning from planetary missions under higher reentry decelerations. Normal cardiovascular effects under high g -levels will be exaggerated for astronauts returning from space, and will occur at lower thresholds. While Shuttle reentry forces do not exceed $1.5g$, they last up to 17 minutes, and could be as provocative as $6g$'s experienced in a fighter aircraft, due to the cardiovascular deconditioning caused by space flight. G-LOC is often preceded by visual symptoms progressing from tunnel vision to grey-out prior to complete blackout, and is accompanied by deficits in motor and cognitive function termed Almost Loss of Consciousness (A-LOC).³⁹ Grey-out is the inability to respond to a light stimulus in the periphery of the field of view, while blackout is a complete loss of consciousness, both being due to loss of blood pressure to the eye/brain with increased $+g_z$ acceleration. The occurrence of G-LOC, A-LOC and related visual symptoms depends on a number of factors, including magnitude, onset rate, and exposure time of the g -load, and is increased with the cardiovascular deconditioning associated with space flight. Well-conditioned humans can withstand a maximum deceleration of about 12 Earth g 's for only a short time, whereas for a deconditioned crew, this maximum is only $3.5\text{--}5g$'s.³⁴ For this reason, the CRV was designed to limit sustained (> 1 second) entry accelerations on crew members to no greater than $4g$'s in the $+/-g_x$ direction, $1g$ in the $+/-g_y$ direction, and $0.5g$'s in the $+/-g_z$ direction.⁴⁰ Maximum g -levels during Earth reentry for flights that landed on moon were $6.63g$, on average. This g -level lasted only for about one minute, followed by seven minutes mostly below $3g$. Earth orbital missions, Apollo 7 and 9, had maximum g -levels of 3.33 and 3.35 , respectively.³²

One device that can be employed to prevent G-LOC and related problems is an anti- g suit (AGS), which is part of the current launch and entry suit worn by astronauts called the Advanced Crew Escape Suit (ACES). An AGS provides positive pressure to the lower torso, preventing blood from pooling in the legs, and may also help to increase venous return. Straining and tensing muscles has long been recognized as an effective method of raising the blackout threshold. In some early aircraft experiments, von Diringshofen⁴¹ found that sustained contraction of all the skeletal muscles increased tolerance by approximately $2g$, which is acceptable for short duration exposures. The M-1 procedure, which involves repeating the Valsalva maneuver every 3-4 seconds, also gives substantial protection by raising blood pressure at head level. However, it tends to be very tiring and distracts the pilot from other tasks. Positive pressure breathing has also been found to improve the ability to withstand high, sustained

accelerations.⁴² While still fatiguing, it was found to be much less so than performing the M-1 procedure or using a g-suit, but can cause difficulty when trying to communicate.

Also of great concern for returning from space flight is orthostatic intolerance, which is characterized by a variety of symptoms that occur upon standing, including lightheadedness, increase in heart rate, altered blood pressure, and fainting. This condition would make rapid egress difficult, especially during an emergency. Orthostatic intolerance affects about two-thirds of the Shuttle astronauts returning from space flight, and so several countermeasures have been adopted to help minimize its occurrence. Astronauts currently drink 1-2 liters of high-sodium liquids before reentry, in order to replace the circulating volume that was lost during the flight. In a sample of 26 astronauts, the 17 who practiced “fluid loading” had lower heart rates, maintained blood pressure better, and reported no faintness, compared to 33% incidence of faintness in the 9 astronauts who did not use the countermeasure.⁴³ However, it appears that the effectiveness of fluid loading is reduced as mission duration increases.⁴⁴ Lower Body Negative Pressure (LBNP) is a countermeasure that stresses the cardiovascular system on orbit by creating a controlled pressure differential between the upper and lower body. This mimics 1g in that the heart responds by increasing blood pressure in order to maintain proper blood flow to the head and upper body.⁴⁵

In addition to the various techniques available for increasing acceleration tolerance, crew vehicle design and cockpit orientation can also influence the magnitude of forces acting on the crewmembers. Any measure which reduces the elevation (with respect to the acceleration vector) between the heart and the brain provides a degree of protection against G-LOC. Similarly, a change of posture that reduces the tendency for blood to pool in the lower part of the body will help to maintain the circulating blood volume, and hence raise the tolerance to acceleration. Gell and Hunter⁴⁶ investigated the degree of supination, or recumbent seating, necessary to give a pre-determined amount of protection. They found that in order to withstand 10g for 5 seconds without blacking out, subjects must be tilted to 85° from the vertical, and that if the angle were only 77°, the gain was no greater than could be achieved with an efficient anti-g suit. The relatively small benefit to be derived from partial supination alone was also noted by Dorman and Lawton⁴⁷, who found that a backward tilt of 65° did not raise the grey-out threshold as much as an anti-g suit in the upright position. When partial supination was combined with the suit, however, a considerable degree of protection was afforded, and all the subjects tested were able to withstand 7g for 15 to 30 seconds without visual symptoms. With postural methods, the choice lies between a failure of vision due to the acceleration and an unacceptable restriction of the FOV because of the posture, but this issue is only of primary concern for those flying

the vehicle. Stewart⁴⁸ and Kerr et al.⁴⁹ showed that the visual impairment was not serious if the degree of tilt were only enough to give about 1g of added tolerance, but that it became progressively more serious as attempts were made to raise the black-out threshold still further. Wiesehofer⁵⁰ recommended that high positive accelerations should be countered by the use of a tipping seat that would automatically throw the pilot in the prone or supine position when the stress was applied. Von Beckh⁵¹ later developed the PALE (pelvis and legs elevating) seat that could automatically rotate a subject about his/her eye point from a seatback angle of 13° to 75° in one second, allowing some subjects to achieve 14g at 75° for 45 seconds without a loss of peripheral vision. This articulating seat achieves supination by elevating the pelvis and legs forward and upwards, while the head and shoulders barely move thus leaving out-of-the-cockpit FOV and vision of displays unchanged, avoiding vestibular symptoms. Recumbent seating was used for deconditioned astronauts returning from long-duration stays aboard the Russian Mir space station, and is currently used for ISS crews returning on the Space Shuttle, but these crewmembers are not responsible for controlling the spacecraft. Some designs for human space vehicles, such as versions of the ISS CRV, have had all crewmembers seated in a recumbent fashion. Depending on the crew's condition and the reentry acceleration profile, a combination of several of the techniques mentioned above may be the best solution for preventing G-LOC and its associated visual symptoms. For example, remaining recumbent from entry interface to landing may be ideal for the cardiovascular system, but not necessary, and could cause problems for other body systems. An upright seating position in combination with other techniques may prove to be adequate. Additional research will need to be conducted to determine the long-term effects of altered gravity upon the cardiovascular system during reentry, as virtually no testing of cardiovascular function has even been performed on Shuttle pilots during reentry.

Landing Impact and Parachute Shock

Since all US spacecraft to date have been unpowered during reentry and landing, reducing both horizontal and vertical velocity in order to decrease landing impact has been an important design consideration. The high L/D Space Shuttle lands on a runway as a glider, and impact loads are minimal. However, with other designs such as ballistic capsules or lifting bodies, this type of landing is not possible. Due to their lower coefficient of lift, these types of vehicles must employ other methods for slowing the spacecraft sufficiently to minimize impact forces.

For a spacecraft that will land using a parachute or paraglider, impact attenuation is a primary concern in

order to avoid injury. Apollo capsules impacted the ocean water at 9 m/s, whereas the Soyuz hits the ground at approximately 7 m/s. The most severe impact experienced in an Apollo space flight occurred with Apollo 12. It was estimated that the Command Module entered the water at a 20 to 22° angle, instead of the nominal 27.5°, which resulted in a 15g impact. This off-nominal impact occurred when the surface winds caused the spacecraft to swing and meet the wave slope at a more perpendicular angle. While the 15g impact of Apollo 12 was described as ‘very hard’ by the crew, no significant physical difficulties were experienced.³² The impact during a Soyuz landing is approximately 4g.

The human body can withstand the greatest impact loads through the chest (+g_x). Tests have shown the following human tolerances to impact: 20g at 10,000 g/s through the chest; 20g at 1,000 g/s laterally through the side; 15g at 500 g/s through the spine.⁵² Thus, if impact forces are a concern, crew position should be considered for reducing the potential for injury, with impact through the axis of the chest providing the greatest protection. For a capsule with a parachute where landing impact and parachute shock can still be high, having crewmembers land on their backs is optimal, as was done for Mercury, Gemini, and Apollo and is still done for Soyuz. The paraglider landing system originally proposed for the Gemini spacecraft caused the capsule to land on its side, placing crewmembers in an upright position. During the reentry phase, the vehicle could be steered to a landing area, and a flare maneuver would reduce the vertical descent rate close to zero, and so having crewmembers landing on their backs was not required. Besides the landing impact concerns for the early capsules and for the CRV, there is also an associated parachute opening shock for each of those designs. It is important to note that the decision to have crewmembers recumbent in the CRV was due not only to impact or cardiovascular concerns, but also to provide adequate room for the crew to ingress and egress the vehicle.^{††}

The ability to withstand deceleration also has to do with the design of the crew restraint system. Stapp⁵³ successfully demonstrated that, using a special restraint system, he was able to endure +x (chest) acceleration levels up to 45.4g, with a rise time of 0.11 seconds and a velocity change of approximately 56 m/s. However, such a restraint system may not be operationally practical, since it would likely be complex to don and severely restrict the occupant’s mobility. Many aerospace designers have proposed that the ideal body support system is a rigid, individually contoured couch, like those used in the early U.S. space program and in the current Russian Soyuz capsule. This approach ensures that each external body segment will be simultaneously decelerated on landing and

^{††} M. Sanchez, Personal communication, NASA Johnson Space Center, December 2003.

that the support pressure gradients exerted on the body surfaces will be minimized. The disadvantages of an individually contoured couch include high cost of individual fitting, and discomfort, because only one body position matches the contour. The contoured shape also makes different types of movement difficult, which would be a detrimental factor for vehicle control. It is also important to consider that the vehicle itself should be the major reducer of impact forces, with the use of retrorockets, stroking/crushable seats and structure. The Apollo Command Module included a stroking seat frame to help attenuate landing impact in case of a parachute failure. The Russian Soyuz uses retrorockets in addition to contoured couches.

With the exception of the Soyuz 1 parachute failure in 1967, impact forces upon return from space flights to date have generally been well within human tolerance limits. These limits, however, may not adequately take into account the compromised condition of a crewmember that has been exposed to microgravity for extended periods of time. The muscles and bones in the lower back, abdomen, and legs that are responsible for maintaining posture and balance are greatly reduced in strength by exposure to weightlessness. Bone loss as high as 20% has been seen in some astronauts after a six-month flight, which could lead to a significant increase in fracture risk upon return to 1g.²¹ It is estimated that +g_x impact tolerance limits for a seated and properly restrained person will decrease from approximately 35g for up to 0.1 second with onset rates of 500-1,000 g/s to 25g at 500 g/s, after hypokinesia due to space flight.⁵⁴ However, even with these reduced tolerances, the proper combination of landing system and vehicle design may be able to ensure landing impact and parachute shock remain within safe limits, and so crew position may not need to be considered for reducing these effects. Table 10 summarizes the discussion of human constraints and design options to ensure the health and safety of the crew.

Table 10 Human Constraints and Design Options

<u>Cardiovascular Distress</u>
Recumbent seating, LBNP, Fluid loading, Procedures (M-1, tensing), Positive pressure breathing
<u>Landing Impact</u>
Recumbent seating, Restraint system, Water landing w/ parachute/parafoil, Land landing w/ parachute/parafoil and retrorockets, Individually contoured couches, Crushable vehicle structure
<u>Parachute Shock</u>
Recumbent seating, Restraint system, Individually contoured couches, Parachute design

Merging Constraints to Create an Optimal Design Solution

Assuming that the crew must provide some vehicle control during descent and landing, the design of a spacecraft must concurrently address and optimally balance all of the effects summarized in Table 11. Individual countermeasures and design solutions have been proposed in the preceding paragraphs to address the different human and mission constraints identified, but the critical issue is whether or not they can all be compatibly implemented. In order to minimize vestibular disturbances, a FOV allowing forward and peripheral viewing with an upright crew position is ideal; reducing cardiovascular distress can be accomplished with an AGS, on-orbit fluid loading, LBNP, or recumbent seating; musculoskeletal injury during parachute opening and landing can be avoided with a proper restraint system, crew couch, crushable vehicle structure, or a recumbent position. It is possible that crew position does not need to be considered for cardiovascular and musculoskeletal problems, but additional research is required. If recumbent seating is mandated, it may still be possible to address mission constraints by using a capsule and parafoil design, and human constraints by appropriately transitioning the crew's position through the various phases of entry and landing.

Table 11 Competing Human and Mission Parameters to Define and Integrate by Design

<u>Parameters Affecting Humans</u>	<u>Spacecraft Design Variables</u>
Spatial disorientation	Pilot control vs. automation
Perceptual illusions	Reentry heating
Vestibular hypersensitivity, misinterpretation	<i>g</i> -loads (ascent & descent)
Tactile hypersensitivity, misinterpretation	Landing accuracy
Cardiovascular deconditioning	Terminal landing method
Visual tracking degradation	Impact loads
Musculoskeletal atrophy	Launch vehicle
<i>g</i> -LOC / <i>a</i> -LOC (magnitude, direction, duration)	Vehicle size, shape, mass
Impact load (magnitude, direction, duration)	Crew position / seat angle
Parachute shock (magnitude, direction, duration)	Field of view
Multiple acceleration phases	Instruments / displays / controls
“Unnatural” inputs	
Training (familiarity/retention)	

Cardiovascular effects are likely to be important from entry interface until landing, but are most critical during transition from 0*g* and during periods of high-*g*. A brief parachute shock would occur at the transition into the descent and landing phase, vestibular disturbances would be most critical during the final descent and landing operations, and impact forces would be encountered at the moment of landing. Assuming the initial atmospheric entry phase is fully automated, head motion can be minimized to reduce provocative vestibular disturbances, and

recumbent crew positioning can be used for the primary benefit of reducing cardiovascular distress. The crew would remain recumbent during parachute deployment to keep the deceleration force acting through the chest, which would protect them from possible g-load injuries. Transitioning the capsule to its side upon parafoil deployment would then provide a crew position to allow for the most reliable visual and vestibular inputs in order to maintain orientation and vehicle control to provide an accurate and soft landing (Fig. 5). The engineering challenge presented by this concept lies in ensuring a smooth transition of the capsule onto its side during parafoil deployment.

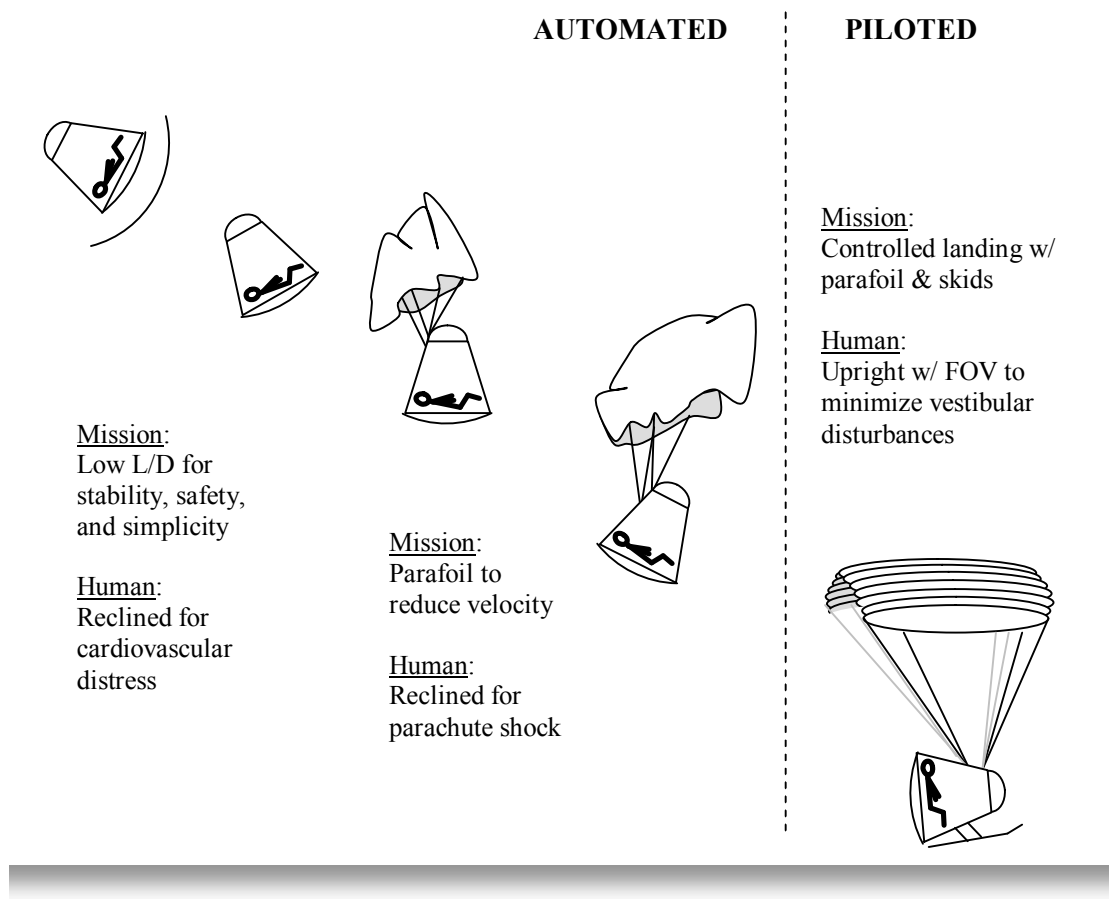


Fig. 5 Example of a Variable Configuration Entry Option for Merging Comprehensive Constraints

Conclusions

Since almost all astronauts experience some level of sensory disturbance during reentry and landing, and since these detrimental effects would likely be exacerbated if traveling in a spacecraft whose design deviates considerably from that of a conventional aircraft, seat position is a critical element to consider in the design of

piloted spacecraft. Furthermore, human constraints should be considered early in the design process, rather than retrofitted at a later stage, and thus prone to unnecessary compromises. An integrated approach to spacecraft design that addresses factors driven by sensory disturbance mitigation, mission constraints, and other human concerns described in this paper, would help to ensure the safety and success of future missions. With the current focus on space exploration within NASA and space tourism in the private sector, the concepts presented here are applicable to numerous immediate and future goals of human space flight.

Future related work should include determining the effects of long-duration exposure to partial-g (e.g., 0.16g on the lunar surface or 0.38g for Mars) on human cardiovascular, musculoskeletal and vestibular systems. Transitioning between these fractional gravity environments and 0g orbital flight, with ultimate high-g reentry and return to 1g on Earth presents unique concerns for piloted spacecraft designs.

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