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MEASUREMENT OF PERFORMANCE USING ACCELERATION CONTROL AND PULSE CONTROL IN SIMULATED SPACECRAFT DOCKING OPERATIONS

Adam R. Brody
Sterling Software
NASA Ames Research Center
MS 262-2
Moffett Field, CA. 94035-1000

Stephen R. Ellis
NASA Ames Research Center
MS 262-2
Moffett Field, CA. 94035-1000

ABSTRACT

Nine commercial airline pilots served as test subjects in a study to compare acceleration control with pulse control in simulated spacecraft docking maneuvers. Simulated remote dockings of an orbital maneuvering vehicle (OMV) to a space station were initiated from 50, 100, and 150 meters along the station's -V-bar (minus velocity vector). All unsuccessful missions were reflown. Five-way mixed analyses of variance (ANOVA) with one between factor, first mode, and four within factors, mode, block, range, and trial were performed on the data. Recorded performance measures included mission duration, and fuel consumption along each of the three coordinate axes. Mission duration was lower with pulse mode while delta V (fuel consumption) was lower with acceleration mode. Subjects used more fuel to travel faster with pulse mode than with acceleration mode. Mission duration, delta V, X delta V, Y delta V, and Z delta V all increased with range. Subjects commanded the OMV to "fly" at faster rates from further distances. These higher average velocities were paid for with increased fuel consumption. Asymmetrical transfer was found in that the mode transitions could not be predicted solely from the mission duration main effect. More testing is advised to understand the manual control aspects of spaceflight maneuvers better.

INTRODUCTION

Historically, in the design of large and complex systems such as aircraft, automobiles, and nuclear power plants, designers typically ignored human factors considerations or left them until too late in the design process to be useful. Controls and displays located outside reach and sight envelopes, inappropriate automation, and operating procedures designed without concern for man-in-the-loop considerations have plagued various industries and led to the loss of many lives, vehicles, and other equipment. These accidents are highly visible in the aviation industry where two-thirds of the commercial aviation incidents and almost 90% of the general caused or influenced by human error.[1]

The Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), Department of Defense (DOD), and the major airline manufacturers are actively involved with investigating the human factors environment of aircraft to identify the means to reduce the likelihood of human error. "At first sight, it is a strange professional link between the aerospace design engineer and the psychologist. Yet, since the days of the Wright brothers, there has always been a need for designers to take human factors into consideration to ensure the efficiency of any flying machine."[2] Two particular concerns are automation and crew coordination and their relationships with flight procedures.

While spaceflight does not put millions of civilians at risk every day, every minor incident receives tremendous attention by the media and the public. On-orbit flight activities put lives, missions, and billions of dollars of hardware in jeopardy. Current and future research into the manual control aspects of orbital flight will have tremendous payoffs in safety, reliability, efficiency, and productivity as space traffic increases in the upcoming Space Station Freedom era.

Spacecraft docking will be a commonplace activity in the era of the space station. Shuttle orbiters, orbital maneuvering vehicles (OMV) (or equivalent), and orbital transfer vehicles (OTV) will be docking to the station. Vehicles will dock with satellites as well to return them to the station. Further into the future, vehicles will be docking in orbit around Mars, in lunar orbit, and on return to Earth orbit. Space Station Freedom will be used as a staging area for assembling and verifying spacecraft en route to the moon and Mars. It will also be used as a repair shop for satellites and a platform for experiments and equipment. These activities will increase the docking traffic at the station further justifying current research agendas. Current state-of-the-art computer graphics has improved real-time simulation and intensive and comprehensive human factors investigations with which researchers can study and better understand these activities.

Very little research describing human factors implications of spacecraft docking operations has been documented in the twenty-five years since the first spacecraft docking.[3-20] Parameters of flight such as approach and impact velocities, braking gates, and control modes must be examined to uncover fundamental human factors capabilities and shortcomings with regard to piloting spacecraft. Results from these studies will assist in expanding the operational flight envelope, and increasing safety and productivity. This study represents another in a series of experiments designed to accumulate a comprehensive database describing the manual control aspects of orbital flight.

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> Practical exploration by man of the nearest regions of space has already developed its own history which consists of separately distinguishable stages. During the first stage, mankind's curiosity concentrated mainly on the technical possibilities of overcoming Earth's gravity. During the next stage, the main focus of study centered on the survival of living organisms, including humans, in space using technical devices. The present stage primarily involves mankind's active work during prolonged spaceflights. Hence, in the short history of astronautics and cosmonautics, the centre of interest has been shifting away from the engineering sciences towards the biological, medical, and psychological sciences. [21] (p. 352)

Along with the psychological studies related to stress and workload are studies concerned with manual control and other areas in the general category of human factors. On Space Station Freedom, crewmembers will be remotely operating vehicles, robots, and experiments subject to the peculiarities of zero-g, orbital mechanics, temperature extremes, and hard vacuum. Current research geared toward uncovering and exploring performance aspects of this environment could have large payoffs in the future.

The importance of manual control aspects of spaceflight operations, such as rendezvous and docking, was recognized early in the United States space program. After only three manned flights in the Mercury Program, the Technical Director, Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson AFB concluded "that men can contribute greatly to the successful accomplishment of many types of space missions. . . . the Mercury astronauts were able to manually compensate [sic] for equipment malfunctions and thereby complete missions which otherwise would have failed or terminated prematurely." [22] (p. 79) As Gemini XII and Apollo XI astronaut Buzz Aldrin explains, "Manned orbital rendezvous was a vital field, because any way you cut it, if we were going to assemble large interplanetary spacecraft, we'd have to master the techniques of space rendezvous—bringing two or more separately launched spacecraft together in orbit. With computers we could reduce the blizzard of spherical geometry and calculus equations down to automated rendezvous procedures. But I'd seen enough autopilots malfunction during my flying career to realize that the spacecraft NASA planned to use for Earth orbital lunar spaceflight would need some kind of manual backup." [23]

The Soviets also value the flexibility that manual control allows in "the capabilities of man to see three dimensions and to evaluate the situation better than a machine for flight conditions that have not been provided for by the program." [15] (p. 804) Gemini X and Apollo XI astronaut Michael Collins advocates manual control as follows, "was this not a noble cause, to build an autonomous capability, to allow a manned spacecraft to roam free of ground control, to compute its own maneuvers? Was not the very name of the game, in manned space flight, to put the pilots in control?" [24] (p. 169) Further justification for manual control may be found in the airline industry where "pilots still manually fly even the most highly automated aircraft, if only to maintain their flying skills in the case that they are called on if the automatics fail." [1] (pp. 293-4)

While automation is and will continue to be an important aspect of manned space flight,

> It is unlikely that the pilot will be eliminated, any more than will the operator of a nuclear power plant. Our society believes that humans should have ultimate responsibility for control of complex systems even if inserting the human degrades overall system performance most of the time. The human is still the ultimate back-up system. While machines that are overloaded fail abruptly, people degrade gracefully under excessive levels of workload. Thus it seems prudent to include human operators, even if only as the sub-system of last resort that can "pull the plug." Furthermore, there are also strong political forces to keep humans employed. [25] (p. 183)

The development

> of rendezvous and docking procedures arose in the evolution of the U.S. space program once the initial exploratory phase (Mercury) had been successfully completed and missions became more ambitious. In the United States, the Gemini program was used to acquire these techniques and develop these technologies, and to give astronauts the practice they needed to get to the moon. Orbital rendezvous procedures were performed as the various Gemini craft tracked and approached their respective rendezvous targets. Gemini demonstrated that "precise flight-crew responses during orbital flight is [sic] critically dependent upon the fidelity of the simulation training received prior to flight" [25] (p. 1) [3] (p. 11).

While simulators were, and are, used extensively for procedure development and training, evidence of their use in human factors studies is virtually non-existent in the literature. Presumably, with the rush to get men to the moon and back before the end of the decade, time, money, and effort spent on such studies was not justifiable. With only 12 operational dockings in the Apollo program, three in Skylab, and one for the Apollo-Soyuz Test Project (ASTP), productivity benefits would not have been realized with the low economies of scale of 16 dockings over 10 years. By the end of the 1990s, space shuttle orbiters will be bringing crew and equipment to Space Station Freedom. By 2010, components of lunar bases and spacecraft will be brought to the station for checkout and assembly. Sorties will be made to investigate and repair satellites and other payloads. A small investment now geared toward a better understanding of manual control aspects of piloting docking maneuvers and other space operations could yield large payoffs in the future in terms of safety, reliability, productivity, and launch costs.

Another justification for the current interest in manual control aspects of spacecraft docking operations concerns the differences in on-board sensors and instrumentation between previous Apollo missions and future spacecraft dockings to the station. As Buzz Aldrin recalls the docking after ascent from the lunar surface, "Our radar and the computers on the two spacecraft searched for each other and then locked on and communicated in a soundless digital exchange." [23] Current plans for Space Station Freedom omit this communication capability as well as a laser rangefinder that was proposed earlier. The rendezvous radar on the space shuttle is limited by a minimum operational range of 80 feet. [27] Ironically, rendezvous and docking operations will be harder to perform twenty years from now than they were twenty years ago because of reduced instrumentation and a paucity of information presented to the pilots.

In addition to discovering approach velocities, braking gates, control modes and other flight procedures that will increase safety, efficiency, and productivity, and decrease fuel use, research into the manual control aspects of space operations such as docking maneuvers has hardware implications. For example, there is a tradeoff between the mass of a space station or satellite docking fixture and the amount (mass) of fuel that will be consumed by a vehicle docking with it. (Although current planning has vehicles berthing with the station via a manipulator arm, rather than docking, this tradeoff may be appropriate for satellite dockings.) Increased strength is paid for with an increase in docking fixture mass. More fuel is needed to control impact velocity when docking with a delicate structure than with a more massive, stronger one. Since launch costs are directly proportional to launch mass, hardware designers are incessantly endeavoring to reduce mass. However, over an operational lifetime, operational costs may be elevated as a result of the increased fuel consumption necessary to dock with a lighter, more fragile target. Human factors studies can produce data concerning the fuel mass/approach velocity tradeoff. Flight simulator experiments can be conducted to analyze quantitatively the effect that impact velocity has on fuel consumption. In this way, the lifetime operational costs can be better understood and long-term benefits will not be sacrificed for short-term gains.

From the Gemini program, there is a historic example of uncertainties in fuel consumption requirements. Ratios of actual fuel consumption to theoretically minimum fuel consumption values varied from 1.52 to 4.28 for the ten rendezvous operations. [24] Clearly, mission planners need to have a better idea of this ratio in order to allocate supplies for any given mission correctly. Research into the manual control aspects of rendezvous maneuvers will help reduce both the absolute value and the variance of the actual/theoretical fuel consumption ratio.

Additionally, a comprehensive study of the impact velocity effect on fuel consumption will also yield the effect on mission duration. In the future, the desire to dock during orbital daylight, an increase in space traffic, and other constraints will make time management almost as important as fuel management. In January 1990, the Long Duration Exposure Facility (LDEF) was within weeks of tumbling out of control and deorbiting when the space shuttle crew rescued it. This is one example where time may be very important and a full understanding of the performance envelope for piloting may be necessary for the success of the mission. Studies can be performed to assess the impact of docking port location, number, and design on time and fuel consumption. In short, a comprehensive and extensive study of manual control aspects of spaceflight can produce many long-term savings of time, fuel, and launch costs while increasing safety and reliability. This is currently a timely research agenda to which greater resources and attention are owed.

BACKGROUND

The first spacecraft docking occurred in March 1966 during the Gemini 8 flight of Dave Scott and Neil Armstrong. Armstrong piloted the docking to the Agena target vehicle. "It was also 100 percent manually flown, not unlike mid-air refueling of airplanes, and it made us pilots feel good to hear Neil report that it had been easy, with no surprises." [24] (p. 180) One half hour after docking, however, a malfunction in the Gemini attitude control system led to uncontrolled tumbling. Armstrong was able to null the motion until he released the hand controller at which point the tumbling restarted. To simplify the problem, he backed the Gemini away from the Agena. This unfortunately aggravated the situation and the rotation rate increased to 300 degrees per second. He was ultimately able to recover control and stop the tumbling solely through manual control of the reentry attitude system. "The whole thing had lasted perhaps ten minutes, but they were the hairiest ten minutes in the space program so far." [24] (p. 182).

"Neil was far and away the most experienced test pilot among the astronauts." [24] (p. 317) His "Right Stuff" piloting skill was also required during the Apollo XI landing when he discovered that the designated landing location was too rough to achieve a safe landing. He then resorted to manual piloting to traverse the craters to a smoother spot. As Armstrong's crewmate Buzz Aldrin recalls,

> At 500 feet, Neil was not satisfied with the landing zone. He took over manual control from the computer, slowing our descent from 20 feet per second to only nine, and then at 300 feet, to a descent of only three and a half feet per second. . . . Neil did not like what he saw below. [23]

Ultimately, of course, the landing was successful illustrating the flexibility of manual back-up without which, the mission most likely would have failed. As Gordo Cooper said after his Faith 7 debriefing, "'. . . man is a pretty good backup system . . . '" [23]. Along with John Glenn's piloting skill in flying the reentry of his Friendship 7 mission when it was thought his heat shield became dislodged, this incident helped to entrench the importance of manual control in the NASA mindset.

Even in the commercial airline industry, where there is far more collective piloting experience than in space, there is an apprehension of automation. Pilots have been known to make comments such as, "In some cases the forces driving technology have caused the design of automated systems which compromise the ability of the pilot to fulfill his responsibilities for the safety of the airplane under his command." [28] (p. 155) Since all NASA pilots come from a jet pilot heritage, comments such as these are relevant for the space program as well.

On Gemini X, in July 1966, John Young "finds [docking] as easy as Neil did on Gemini 8." [24] (p. 211). Dockings were also performed on Geminis XI, and XII in September and November respectively. Apollos 9 and 10 practiced orbital docking operations with the Apollo configuration in 1969. (See [3] for a detailed description of Apollo rendezvous and docking procedures.)

Despite the flexibility and resourcefulness that crewmembers provide, it must be admitted that they also supply additional means for malfunction and error.

CURRENT STUDY

Docking maneuvers have traditionally been simulated and ultimately performed in a "pulse" control mode. That is, thrusts of a prescribed magnitude (duration) were commanded by deflection of a hand controller regardless of deflection angle or duration. Subsequent burns were only possible after release of the joystick to its rest position. NASA space shuttle pilots and orbital maneuvering vehicle (OMV) pilots currently are instructed to use pulse control presumably for fuel consumption and safety reasons.[27, 29]

Nevertheless, all previous experimentation by the authors involved acceleration control in which thruster commands were sent for the duration of the deflection.[3-8] This study involved a formal comparison between pulse control and acceleration control to determine which is better for fuel consumption, mission duration, safety, and other considerations.

In the current study, the trials were organized in an APPA and PAAP orders where A denotes a series of 18 simulated dockings using acceleration control and P corresponds to a series with pulse mode. Subjects who began with acceleration mode, continued with two blocks of pulse mode before returning to their final block with pulse mode (i.e., APPA). Subjects beginning with pulse mode did the opposite (i.e., PAAP).

One of the intents of this format was to unearth any asymmetrical transfer that may be present. Asymmetrical transfer would be evident if a control mode x order (mode x first mode) effect were found.[30] It specifically means the effect of practice with one control mode on subsequent performance with the other control mode is different for the two possible sequences of activity (i.e., a PA sequence vs. an AP sequence). This could occur, for example, if subjects who began with pulse mode achieved lower mission duration values when they later flew in acceleration mode than those who began with acceleration mode and followed with pulse mode. Such a finding would be useful for identifying which control mode to use for training as opposed to flight. Additionally, a control mode x range interaction would indicate which mode were better depending upon initial range of the mission. Preliminary data indicated that learning might be easier in pulse mode but better performance characteristics are achieved with acceleration control. Asymmetric transfer effects can also cloud comparison of control modes since the subjects' asymptotic performance may not be accurately reflected by the experimental data.

METHOD

Nine commercial airline pilots served as paid test subjects in this study. Pilots were used because of the expectation that the manual control, attention, discipline, and intelligence skills typically associated with flying would enable them to be superior subjects. In purely subjective terms, however, they performed no better than any other previous group of simulated spacecraft pilots. For example, neither learning nor performance was consistently better than previous groups of subjects.

The study was performed in the Space Station Proximity Operations Simulator at NASA Ames Research Center. This facility simulated a proximity operations control room on a space station. A PDP 11/60 computer in conjunction with an Evans and Sutherland PS II picture system drove three windows. These windows displayed a simulated view out the -V-bar (negative velocity vector) of a space station in a 270 nautical mile circular orbit around the Earth. An accurate star field was visible with representatives down to the fifth magnitude.

A three-degree-of-freedom displacement hand controller was used to command thruster firings on an orbital maneuvering vehicle (OMV) remotely. Buttons on the hand controller were used to control the thruster characteristics for each coordinate axis independently. Thruster values were toggled among 1.0, 0.1, and 0.01 m/s. The subjects used a joystick-mounted trigger to begin each trial.

A head-up display (HUD) containing flight data was superimposed on the center window. Mission duration, velocity increment, 3-axis range and rate, slant range and rate, and thruster values were presented to the subjects.[18-20]

Test subjects performed simulated docking maneuvers of an OMV to a space station from three different ranges on the -V-bar. Each subject used both control modes in blocks of 18 consisting of 3 ranges (50, 100, and 150 m) x 6 repetitions in a latin squares configuration. Five subjects began with acceleration control and 4 began with pulse control. A test session consisted of two blocks with each control mode. The blocks were arranged in an APPA or PAAP order. This yielded a total of 72 trials for each subject. Experimentation required about five hours per subject.

RESULTS

Five-way mixed analyses of variance (ANOVA) with one between factor, first mode, and four within factors, mode, block, range, and trial were performed on the data. All statistically significant effects at the .05 level for the complete data set are summarized in the following table. Trial refers to consecutive presentations of identical experimental treatments. Mode, range, and block are the same for a group of six trials. Block distinguishes between both groups of 18 consecutive trials with the same control mode. The blocks were designated first half and second half.

Table I: Significant effects from ANOVA.

Dep. Var.	Significant Factor(s)	F	p
Mission Duration	Mode	12.544	.0094
	Range	24.156	.0001
	Trial	4.143	.0046
	Mode * Block * 1st	5.835	.0464
Velocity increment	Mode	6.431	.0389
	Range	34.57	.0001
	Block * range	5.792	.0147
	Mode * bl * r * tr * 1st	2.100	.0357
X Velocity increment	Block	7.118	.0321
	Range	31.344	.0001
	Trial	2.653	.0390
	Block x range	5.864	.0141
Y Velocity increment	First Mode	31.523	.0008
	Range	6.861	.0084
	Range * First Mode	6.721	.0090
	Mode * Range * Trial	2.308	.0208
	Mode * r * tr * 1st	2.287	.0219
	Mode * bl * r * Trial	1.984	.0481
	Mode * bl * r * t * 1st	2.018	.0441
Z Velocity increment	Range	4.142	.0429
X Rate	Trial	2.759	.0334

Control mode produced statistically significant, but opposite, effects on mission duration and Δv. Mission duration was lower with pulse mode while Δv was lower with acceleration mode. Subjects used more fuel to travel faster with pulse mode than with acceleration mode. As in more mundane, Earthbound, linear environments, greater velocities, leading to reduced mission durations, are paid for with increased fuel consumption. Although the subjects were trained to criterion, further training could most likely be used to reduce mission duration and/or fuel consumption levels. These results give some indication of what the underlying tendencies are before extensive training.

Mission duration, velocity increment, X velocity increment, Y velocity increment, and Z velocity increment all increased with range. Subjects commanded the OMV to "fly" at faster rates from further distances. These higher average velocities were paid for by increased fuel consumption.

Z velocity increment, the cumulative total of thrusts used to correct for orbital mechanics effects, increased with initial range. This increase was due to the increase in mission duration with range. More fuel was required to compensate for the orbital mechanics effects when more time was given for them to operate.

The most unusual range effect was the one reflected in Y Δv. The y-axis was the out-of-plane component. Since motion along this axis is uncoupled from motion along the other two axes, an object with zero y displacement with respect to a target needs no attention. Although the trials in this study were initialized so that no thrusts along the y-axis were required, accidental commands were made from which recoveries had to be made to achieve a successful docking. Most likely, the longer mission durations associated with the greater initial ranges provided the subjects with more time in which to cause a y disturbance.

Although the subjects practiced to criterion before experimentation, a practice effect in which subjects improve with experience was still evidenced in the data. Mission duration decreased with trial in a typical learning curve format. Surprisingly, X velocity increment increased with experience. This effect was most likely due to subjects becoming more comfortable with the simulated docking maneuver and consequently using more fuel to travel faster.

The X velocity increment data demonstrated a block effect also. Fuel consumption along the x-axis was less in the beginning of testing than in the end. Values from the first eighteen trials with a mode were less than those from the second half with means (SDs) of 7.7 (4.9), and 8.9 (6.1) m/s for the first half and second half respectively. This effect was similar to the trial effect with fuel consumption and velocity increasing with experience. It shows the trend following experience not only within blocks as with the trial effect but also between blocks as mentioned here.

Three 2-way interactions, two 3-way interactions, two 4-way interactions, and two 5-way interactions also resulted from the data analysis. Higher order effects are typically difficult to decipher. Of particular interest are the ones containing a mode or first mode term.

The mode x block x first mode interaction for the mission duration data appears in Figure 1. It shows that the main effect relationship between the modes, namely, the mean for mission duration in pulse mode is less than the acceleration mean only holds for the first half of the data. In the second half of the data, the pulse data for subjects who began in acceleration mode has the same mean as the data from those subjects who began in pulse mode.

The error bars indicate that the data for blocks 2 and 3 for both sets of subjects are not distinct. Essentially, mission duration values for the middle two blocks are the same for both modes. There is also no statistically significant distinction between the data from blocks 1 and 4 in the PAAP group. However, the mission duration mean for block 4 is lower than that for block 1 in the APPA group. (See Figure 1.)

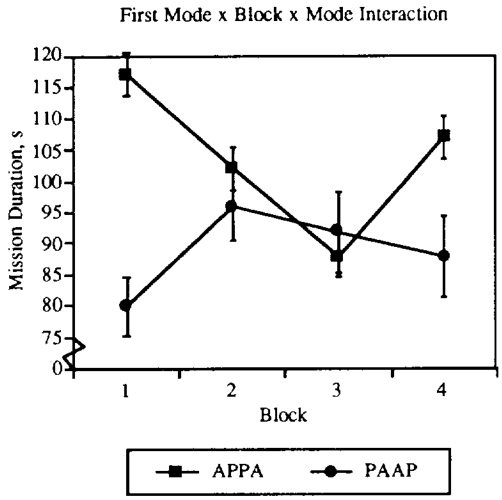

Figure 1: Mission duration 3-way interaction illustrating asymmetrical transfer.

No improvement in mission duration was found for the subjects who began with pulse mode while the data from the acceleration first group display learning. These data support the experimental hypothesis that experience in pulse mode helps performance in acceleration mode. Asymmetrical transfer was found in that the mode transitions could not be predicted solely from the main effect. Both acceleration means in the PAAP group were lower than both acceleration means for the APPA group. The last pulse mission duration means for both subject groups were equal (i.e., block 3 in the APPA group and block 4 in the PAAP group).

Analysis of the transitions between consecutive blocks also yielded interesting results. Both PA transitions were of the same positive slope. While this is illustrative of the main effect, (that is, pulse mission duration lower than acceleration mission duration), only one of the AP transitions was significantly downward. The single PP transition was downward, again indicating a learning benefit from a previous experience with pulse. Conversely, the single AA transition was unchanged.

An ANOVA was performed on the data collapsed across block and trial to determine which combinations of independent variables were more likely to cause an unsuccessful mission. No statistically significant effects were uncovered. Neither mode was found to be inherently safer than the other. No combination of range and mode was more conducive to errors than any other.

DISCUSSION

The finding that fuel consumption levels, measured as velocity increment or Δv, were lower in acceleration mode than in pulse mode corroborates the results from the preliminary experimentation. Pulse mode is not inherently more fuel conservative than acceleration mode as one might presume from studying the appropriate NASA manuals.[1, 2] This indicates that fuel can be used more efficiently in acceleration mode than pulse mode in a docking operation. This is probably due to the greater dynamic range with acceleration control allowing for greater flexibility and fine tuning capability.

The asymmetrical transfer discovered here is important for researchers investigating the impact of control modes on spacecraft docking operations. This result should be regarded as a forewarning that investigators should be careful when designing experiments and formulating conclusions. The asymmetry illustrates an inconsistent main effect for which one must account before attributing a result to a control mode. In comparing different control modes, experimenters should be sure to provide sufficient intervening practice to prevent the effects of asymmetrical transfer from contaminating the experimental results.

The data from this study demonstrated that dockings could be performed faster, albeit at the expense of greater amounts of fuel, in pulse mode than in acceleration mode. While the absolute values of time and fuel were specific to the thruster values that were used, this relationship should be preserved with different thrusters. A whole assortment of studies could be performed to examine the effect that thrusters with different magnitudes from the ones simulated here have on the data. An interaction between thruster size and range might also be revealed. What is clear, however, is that pulse mode is not definitively more fuel efficient than acceleration mode in all situations. Probably the most necessary conclusion to be made at this point is the requirement of further human factors and manual control experimentation before flight protocols are generalized for all vehicles in all situations.

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