SpaceDock: A performance task platform for spaceflight operations

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Abstract

Background: Preliminary evidence during both short- and long-duration spaceflight indicates that perceptual-motor coordination changes occur and persist in-flight. However, there is presently no in-flight method for evaluating astronaut performance on mission-critical tasks such as docking. We present a portable platform we have developed for attempting and evaluating docking, and describe the results of a pilot study wherein flight novices learned the docking task.
Methods: A dual-joystick, six degrees of freedom platform—called SpaceDock—was developed to enable portable, adaptable performance testing in a spaceflight operations setting. Upon this platform, a simplified docking task was created, involving a constant rate of approach towards a docking target and requiring the user to correct translation in two dimensions and attitude orientation along one dimension (either pitch or roll). Ten flight naïve subjects performed the task over a 45 min period and all joystick inputs and timings were collected, from which we could successfully reconstruct travel paths, input profiles and relative target displacements.
Results: Subjects exhibited significant improvements in docking over the course of the experiment. Learning to compensate for roll-alterations was robust, whereas compensation for pitch-alterations was not in evidence in this population and relatively short training period.
Conclusion: The SpaceDock platform can provide a novel method for training and testing subjects, on a spaceflight-relevant task, and can be used to examine behavioral learning, strategy use, and has been adapted for use in brain imaging experiments.

Keywords: spaceflight, docking, behavioral measure, software platform

Introduction

Numerous performance tasks have been developed that test effects of environmental stressors on mental performance {AGARD, 1989 #3481}{Englund, 1987 #3482}(Kennedy *et al.*, 1987; Shingledecker, 1984). These assessment batteries have been largely applied to the industrial and aviation environments. There is not, however, in general use a platform for objective assessment of performance oriented to the specific needs of the spaceflight environment, in which a complex spectrum of stressors can adversely impact crewmember performance. While microgravity is likely the most unique stressor of spaceflight, sleep deprivation, fatigue, circadian desynchrony, confinement, minor trauma, and discomfort from the physiological adaptation symptoms (headaches, nausea, and upper airway congestion) are also exposures that can negatively affect mental performance during space missions.

Past assessment tools have compared in-flight performance on a specific task to a pre-flight baseline. In-flight tasks have included accuracy in intentional limb movement, mental rotation, grammatical reasoning, short-term memory scanning, and joystick controlled compensatory tracking (Fowler *et al.*, 2000). Manzey, in a review of spaceflight mental performance monitoring, summarizes the conclusions gained in these studies (Manzey, 2000), finding that perceptual motor performance appears to decline in spaceflight, particularly early in-flight (when space motion sickness is an added element to environmental stressors) and appears to be one of the most sensitive indicators of mental performance (Newman and Lathan, 1999). Decrements in higher cognitive tasks, such as object rotation and grammatical reasoning, however, have not been detected, perhaps due to lack of sensitivity of the assessment task (Fowler and Manzey, 2000). The correspondence between performance on these simplified tasks to performance on complex, mission-critical maneuvers is not clearly established.

A potential use of in-flight performance measurement tools, besides their investigational value, is in assessment of crewmember readiness before attempted execution of critical procedures. The primary goal of the performance assessment tool described here is to measure perceptual motor skills and higher cognitive function, using a task that not only offers direct relevance to spaceflight but also is easily packaged for transport aboard spacecraft for in-flight use (Manzey, 2000). The implemented task is based on the orbital docking of two spacecraft, a particularly difficult and critical spaceflight maneuver. Manual dockings have been frequently performed during space missions, most commonly the docking of Progress cargo vehicles to the space station Mir or the International Space Station (ISS). Crewmember well-being and mission success can hinge on its precise execution, as evidenced by the 1997 Progress collision with the Mir Space Station, which resulted from a failed orbital docking attempt (Ellis, 2000).

The software described here simulates proximal operations spaceflight docking with up to six degrees of freedom, and is intended to enable the measurement of the parameters of primary importance in successful completion of the docking maneuver. Such parameters include, but are not limited to: 1) accuracy in the final docking orientation, velocity and stability over all degrees of freedom, 2) minimal fuel use during approach, as determined by the total number of subject inputs, and 3) completion of the task in the minimal amount of time. The platform can be used simply for docking practice, to evaluate sensorimotor coordination, and/or can be easily repeated within an experimental paradigm for research purposes. Here, we describe our general-purpose platform—called SpaceDock—that can be used to test perceptual-motor, and cognitive skills unique to docking maneuvers, and present the results from a pilot study of aviation-naïve subjects (no aircraft or spaceflight experience) learning the task.

Materials and Methods

SpaceDock Platform

Programmatic control of the platform is achieved via scripts written in the Python programming language, a relatively easy-to-learn high-level language capable of object-oriented program design {Lutz, 1996 #3483}. To achieve both high animation rates and flexible user-input options, the platform makes use of both the VPython (Scherer *et al*., 2000) and wxPython libraries. VPython is a 3D graphics rendering environment originally developed at the Carnegie Mellon University Department of Physics. It allows high frame rate animation of 3D objects, which can be coupled to and controlled by a Python script for user interaction. wxPython is a set of Python bindings to wxWindows (Zeitlin, 2001), a cross-platform graphical window manager. In the present implementation, the wxPython bindings are used to detect and handle all user interaction. The cross-platform nature of all three programming components allows the task to be ported to most common operating systems. For the task reported here, a simplified docking target is displayed on a portable computer (Toshiba Satellite; Pentium III with NVIDIA GeForce2 Go 32Mb graphics card), and dual joystick inputs by the user provide the illusion of movement of the subject's field of view (FOV) through free space with six degrees of freedom.

The docking task requires the subject to maneuver his or her own FOV as if the subject is the operator of a spacecraft approaching a (typically) fixed target. The magnitude and direction of FOV movements correspond to the subject's keyboard or joystick inputs. The docking target we selected is a devolved model of a docking target universally used in Shuttle payload and ISS docking procedures, illustrated in Figure 1. The cylindrical body is attached to a horizon bar that permits visual detection of induced roll, and to a docking ball and pin that permit visual detection of pitch and yaw alterations. This particular target provides a reasonable balance between sufficient visual detail for identifying the target orientation at a distance, and excessive computational demands, however any target composed of simple 3D geometric shapes can be implemented. A starfield background enhances the attitude change illusion, and allows the operator to visually distinguish his or her own attitude changes from attitude changes of the target alone. For the experiments reported here, a custom, USB-based dual-joystick interface was also developed, wherein joystick directional inputs (six per joystick) were converted to key-presses in hardware. Each joystick provides input for three degrees of freedom via left-right motion, forward-backward motion, and thumb and forefinger buttons (right=x/y/z, left=roll/pitch/yaw). The wxPython window manager captured the twelve potential directional inputs. The joysticks were also designed to be operable within a magnetic resonance imaging environment, to afford research on the neuronal activation patterns induced by the docking task.

Subjects viewed the target on the computer screen, and used the dual-joystick interface to control their FOV from any initial position in the virtual 3D space, to the docked position. "Docked" is defined as the point where the target is both centered and oriented upright (horizon-line horizontal, docking pin pointed straight out of the PC screen towards the user). The reaction of the FOV to joystick inputs was designed to match that of inertial changes in the user's FOV as would be experienced in a gravity-free environment, neglecting orbital mechanics. (Other FOV dynamics are easily incorporated into the Python script). A single joystick input induces an associated FOV velocity, and continuous input results in linear "acceleration" of the FOV. Once relative movement is induced, an equal and opposite input must be made in order to stabilize the FOV with respect to the target.

The software records the following information at the beginning and end of each trial, as well as at each user-input: simulation time, position and attitude data for both the FOV and the target, thruster amplitudes for all six degrees of freedom of both the FOV and the target (for mobile targets), and trial/run information. From this data, one can extract a wide variety of performance metrics post hoc.

Subjects

The study was approved by the Institutional Review Board of the Massachusetts General Hospital, where the experiments were performed. All subjects gave their written informed consent prior to commencing. Ten subjects participated (age range: 23-40), and none had prior aviation or spaceflight experience.

Behavioral Protocol

Subjects first underwent a ten-minute familiarization session with the SpaceDock task by controlling their FOV movement to experience the response characteristics of target movement for a given input. Then, in each of nine runs, the subjects attempted to align the docking target with a constant, predefined position in the center of the screen, known as the "docked" position. Each experimental run consisted of two blocks of four docking trials each, with the blocks separated by 30 sec rest periods. Trials were conducted so that the image of the target appeared to approach the subject's FOV at a constant rate, and the approach speed ensured that each trial was 30 seconds in duration, from trial initiation to point of closest approach. The subjects were given complete control over x-y translation and pitch-roll attitude of their own FOV (and hence of the target within the visual plane perpendicular to their view).

The target's initial position in each trial was randomly chosen from the list of target positions and orientations found in Table 1—all of which are equidistant from the subject's FOV—and comprise a single attitude misalignment relative to the FOV. Therefore, for each trial, the subject had to make both translational and attitudinal corrections to properly align the target within their FOV.

Table 1: Initial conditions for docking target.

Target #	X (a.u.)	Y (a.u.)	Z (a.u.)	Roll (deg)	Pitch (deg)
1	2	4	16	-25	0
2	4	2	16	0	-25
3	-2	4	16	0	25
4	-4	2	16	25	0
5	2	-4	16	0	25
6	4	-2	16	25	0
7	-4	-2	16	0	-25
8	-2	-4	16	-25	0

Data from the familiarization session was not analyzed. While any number of behavioral metrics can be extracted, for each of the eight trials in each of the nine experimental runs the following measurements were calculated: 1) the final distance of the target from the desired "docked" position at the moment of closest approach to the FOV, 2) the angular error at the point of contact, and 3) the total number of keyboard inputs (an approximation to fuel use). These measures were chosen for their operational relevance. While the time to reach the docked position is also relevant in a real flight setting (flight operations following a strict timeline) the study presented here involved a constant rate of approach to provide experimental control over the behavioral timeline. All values were analyzed by standard linear statistical methods to test the sensitivity of each measure to detect learning-related changes in novice flyers.

Results

The recorded information allows full reconstruction of each subject's trajectory and responses throughout the experiment. In Figure 2 we show our first subject's trajectories for the first target location (see Table 1) during each of the nine runs. In Figure 2A we plot the X-Z axis projections of these trajectories, and Figure 2B we plot the Y-Z projections, where thicker lines indicate earlier runs. In this example—particularly in Figure 2A—one can see unnecessarily wide excursions in the early trials (arrows), and for the very first trial this excursion was never fully corrected (leftmost arrow). The initial overshoot progressively improved such that later trials approach the point (0,0) nearly linearly. Similar wide excursions are also seen in Figure 2B, which are again disappear by the later trials.

Figure 3A shows the error in the final position over nine runs (for figure clarity, only two subjects are shown). Figure 3B shows the total number of keystrokes (our approximation for fuel use) over the nine runs for the same two subjects. In each case, points are plotted at the average over eight trials per run for a given subject, while the errorbars indicate the standard error of the mean for the same eight trials. When comparing the initial pair and final pair of runs, improvements in both accuracy and fuel use were significant both for subjects shown (Subject 1: $T=3.3$, $p=0.002$ and $T=4.7$, $p<0.0001$, respectively; Subject 2: $T=3.2$, $p=0.003$ and $T=8.1$, $p<0.0001$). Nine of 10 subjects showed significant improvements in accuracy, whereas seven of 10 subjects showed significant reductions in fuel use.

Next, we first computed the average distance error and total number of inputs across subjects, the results for which appear in Figure 4A and Figure 4B. In this case, the points correspond to an average over our 10 subject's mean final position error (and total keystroke count), and errorbars represent the standard error of the mean across subjects. The substantially increased variability in Figure 4 relative to Figure 3 highlights the large inter-individual differences in these measures, as would be expected (particularly in flight naïve subjects). However, one-way ANOVAs examining the changes over time were significant for both translation error ($F(8,64)=4.2$, $p<0.0001$) and resource utilization ($F(8,64)=2.8$, $p=0.01$).

Another indicator of accurate performance on this docking task—beyond translation error and resource use—is the attitude/angle error. Initial examination of average attitude discrepancies from the target at the point of contact indicated no significant improvement occurred across the nine experimental runs ($F(8,64)=1.3$, $p=0.25$; data not shown). However, further investigation found that the two types of trials—roll and pitch displacement—were not of equal difficulty. The aviation-naïve subjects exhibited significant roll-error improvement over time ($F(8,64)=9.7$, $p<0.0001$). In contrast, the average pitch error remained constant throughout the experiment ($f(8,64)=0.7$, $p=0.7$).

Discussion

A portable-computer based docking task—called SpaceDock—was developed that can be used to assess perceptual-motor and cognitive performance. The task is relevant to spaceflight operations in that it can potentially assess performance in the specific skills necessary for completion of a space-unique, mission-critical task. These skills include situation analysis, planning, decision-making, object orientation, mental rotation, visual processing, fine motor control, and visual-motor integration. The experimental data presented here indicate that even our relatively simple version of the task (requiring a subject to control only one attitudinal and two translational and degrees of freedom per run) produces a significant learning curve—across the 72 separate docking attempts—in aviation-naïve subjects. The resulting data helped elucidated control strategies (e.g., Figure 2), which would likely differ between naïve and expert flyers, and enabled the identification of trial types of differing difficulty and learnability (roll vs. pitch).

The SpaceDock platform allows presentation of single or multiple performance assessment scenarios with continuously adjustable difficulty levels. At the simplest level, the target's initial conditions can be changed to include any static position or attitude. A more complicated task is to give the target an initial translation or attitude velocity that must be compensated for by the operator prior to successful docking. This would allow for the examination of mental rotation and on-line planning. Advanced levels of difficulty can be presented through a sustained bias in one of the degrees of freedom in either the FOV or the target, equivalent to the problem presented to the operator by a reaction-control jet that is "stuck" on. If the target bias is in the direction towards the operator, the simulated constant target approach velocity may be used to induce time pressure on the subject during the docking task. All of these tasks carry operational significance and have an historical basis in spaceflight. Instability of the target vessel through malfunction of reaction-control jets has occurred, inducing movements in the target similar to what can be presented in this task. In at least two episodes, the cargo and target vessels had initial approach rates greater than could be controlled by the operator, simulated here with target approach independent of user inputs. And, this ability to reconstruct the entire flight trajectory allows for post-hoc extraction of performance metrics suitable to the investigation of a wide variety of research questions.

Future experiments will compare the performance of naïve subjects to veteran aviators, as has been done with flight simulator tasks (Peres *et al*., 2000). The joystick design also allows the task to be implemented in a brain-imaging environment, for which experiments are underway (Strangman *et al*., 2003). It is believed that such a task platform will provide a relevant and accurate measure of spaceflight perceptual-motor and cognitive performance, and it's similarity to actual docking systems will make it useful to the spaceflight community.

SpaceDock Flexibility

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Figure Captions

Figure 1: The docking target for the SpaceDock task.

Figure 2: Path data for each of 9 equivalent runs from an example subject.

Figure 3: Final position and total inputs data to each of two example subjects.

Figure 4: Distance-error, roll and pitch attitude-error at moment of closest approach for each of 9 runs (n=10 subjects).

Figure 5: Distance-error, roll and pitch attitude-error at moment of closest approach for each of 9 runs (n=10 subjects).

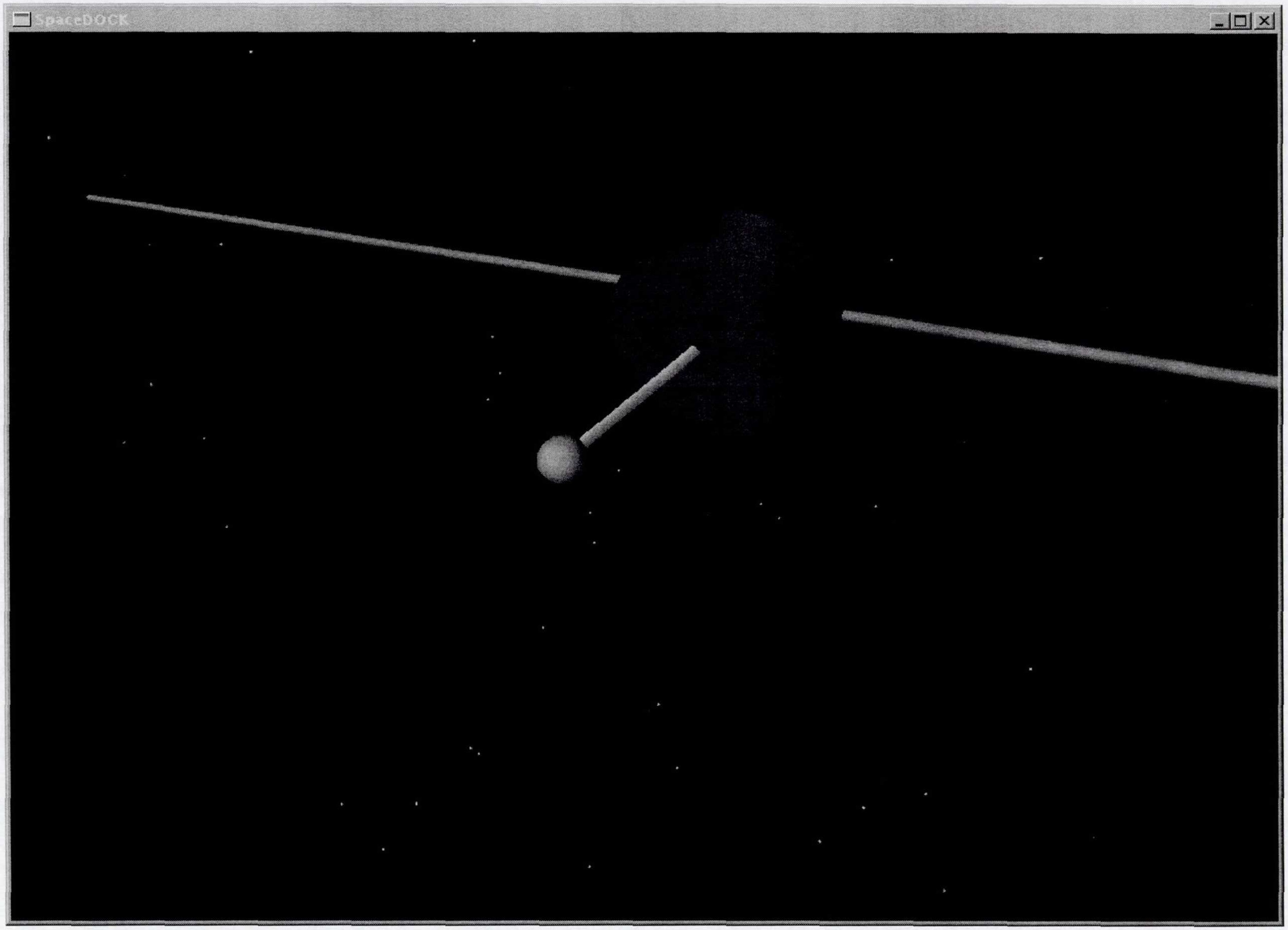

Figure 1

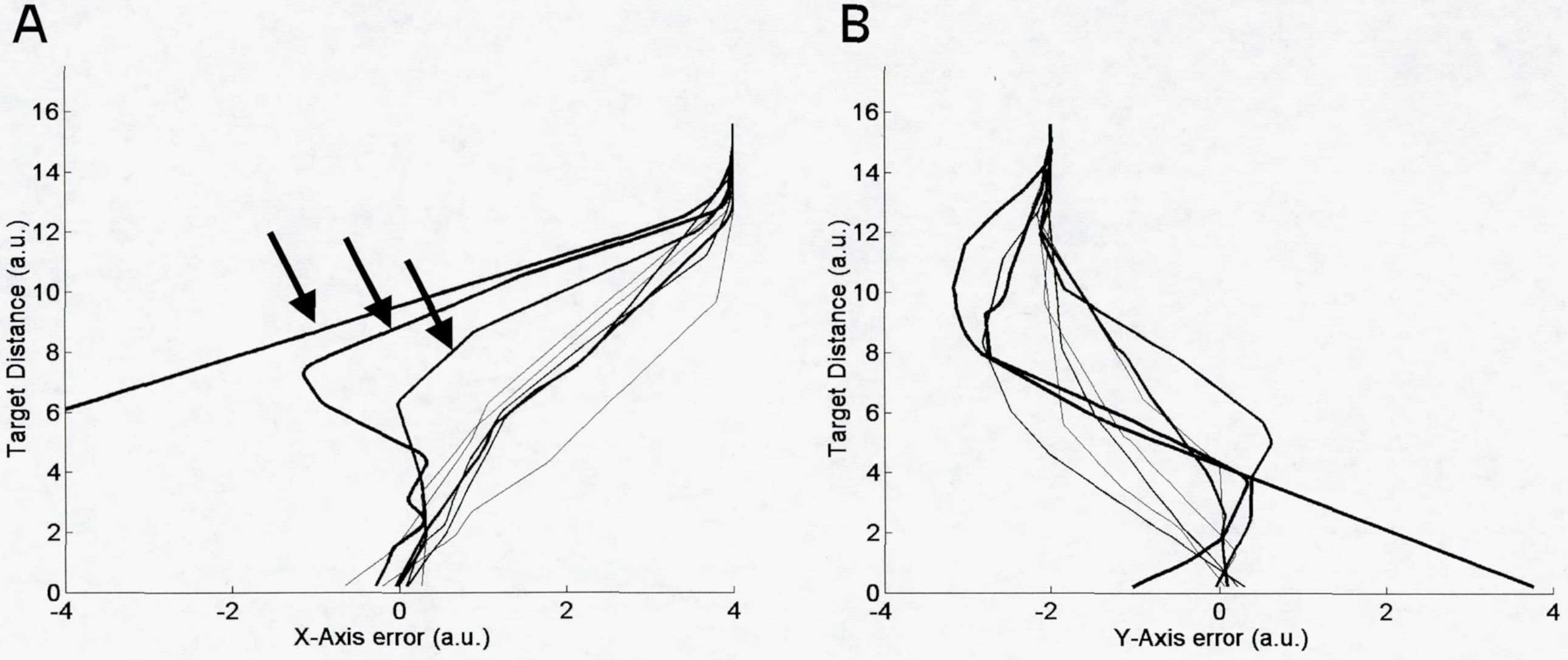
A
B
Target Distance (a.u.)
0
2
4
6
8
10
12
14
16
-4
-2
0
2
4
X-Axis error (a.u.)
Y-Axis error (a.u.)

Figure 2

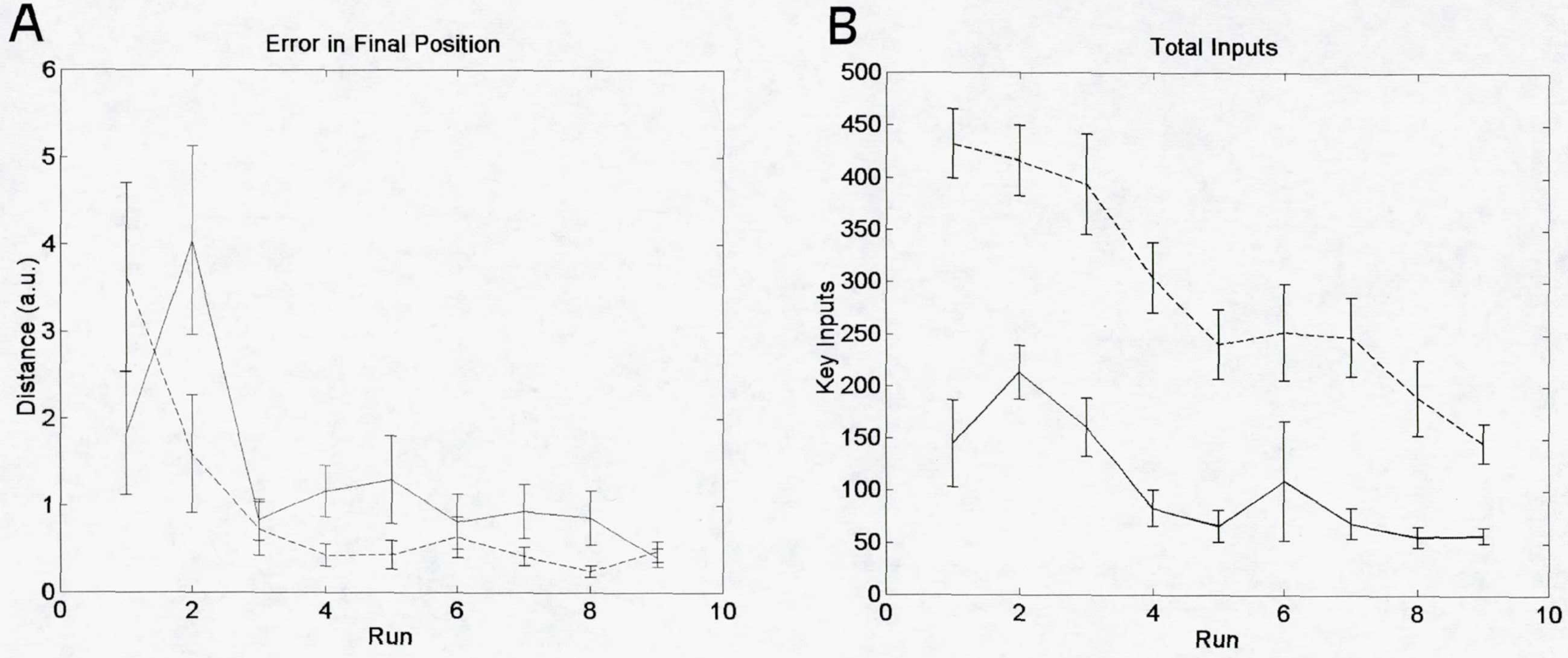
A
Error in Final Position
Distance (a.u.)
0
1
2
3
4
5
6
0
2
4
6
8
10
Run
B
Total Inputs
Key Inputs
0
50
100
150
200
250
300
350
400
450
500
0
2
4
6
8
10
Run

Figure 3

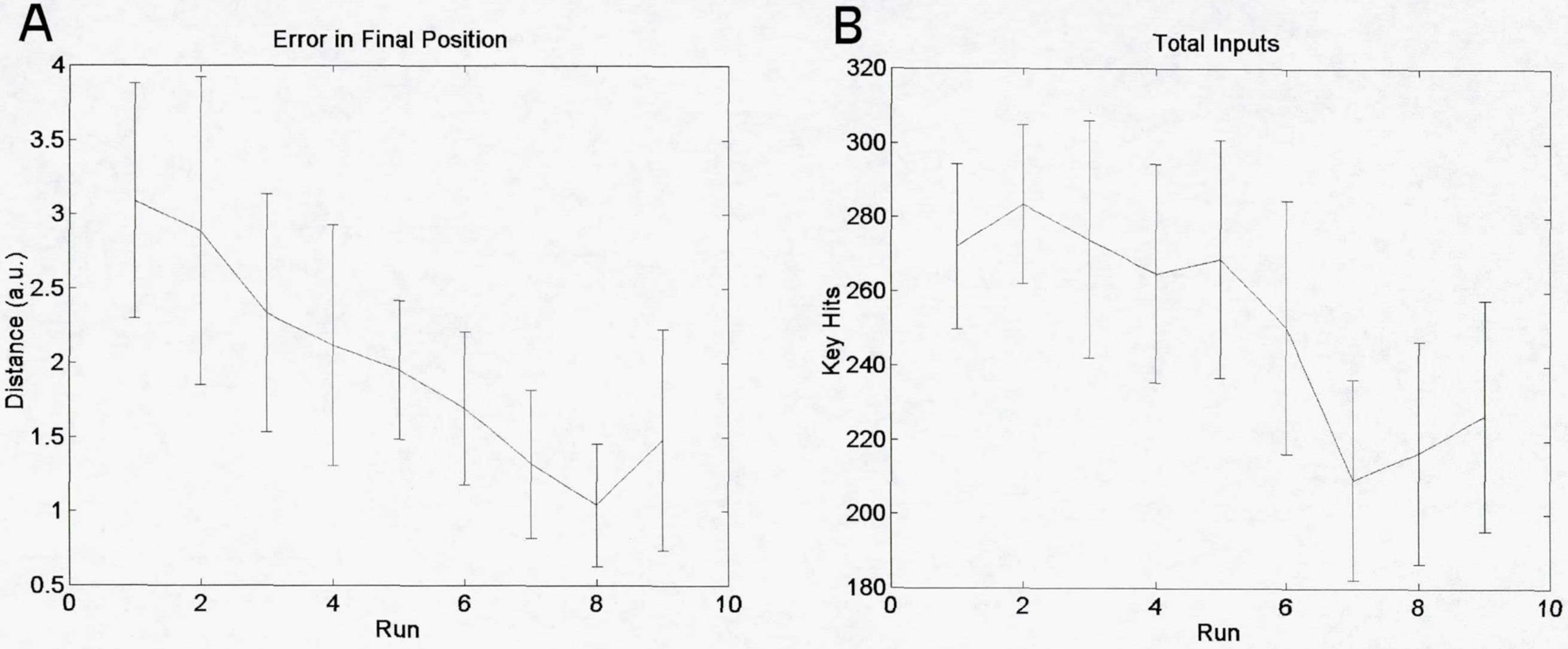
A
Error in Final Position
Distance (a.u.)
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
Run
B
Total Inputs
Key Hits
320
300
280
260
240
220
200
180
0
2
4
6
8
10
Run

Figure 4

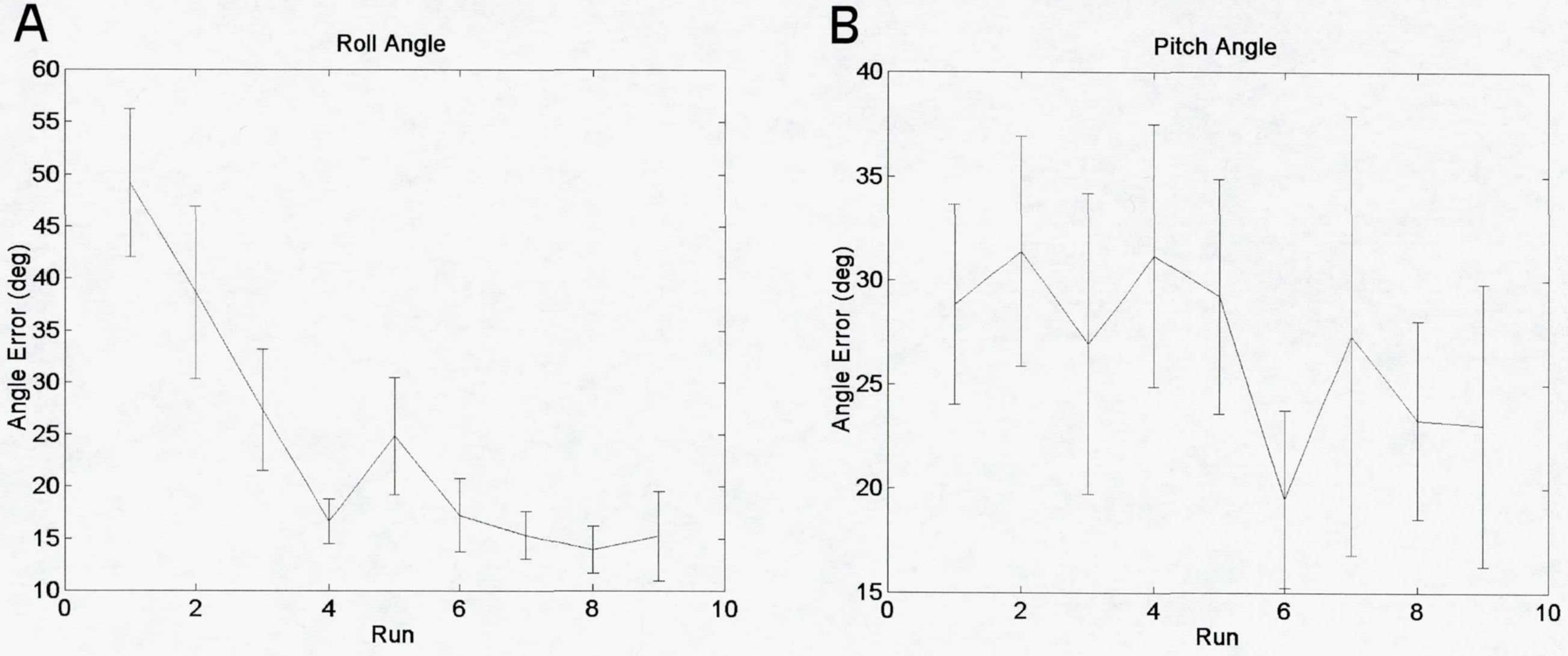
A
Roll Angle
Angle Error (deg)
60
55
50
45
40
35
30
25
20
15
10
0
2
4
6
8
10
Run
B
Pitch Angle
Angle Error (deg)
40
35
30
25
20
15
0
2
4
6
8
10
Run

Figure 5