

Galvanic Vestibular Stimulation as an Analogue of Spatial Disorientation After Spaceflight

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Background: Exposure to microgravity adversely affects performance of astronaut pilots; a review of the first 100 Shuttle missions found that touchdown speed was above specified limits in 20% of landings, in contrast to near ideal performance in preflight high-fidelity Shuttle simulations. Ground-based simulators emphasize spacecraft handling abilities, but do not recreate the effects of extended weightlessness on sensorimotor function. The aim of this study was to validate an analogue of the sensorimotor effects of microgravity using pseudorandom bilateral bipolar galvanic vestibular stimulation (GVS) during Shuttle landing simulations. **Methods:** Pilot performance was assessed during simulated Shuttle landings in the Vertical Motion Simulator at NASA Ames Research Center, Moffett Field, CA (used for astronaut pilot training). Subjects ($N = 11$) flew eight pairs of identical landing profiles (final approach and touchdown), with and without GVS, presented in a pseudorandom order. **Results:** Touchdown speed was on target (204 kn) without GVS [203.8 kn], but increased significantly during GVS exposure [208.5 kn] and was at the upper limit (209 kn) of the target range. The adverse effects of GVS on pilot performance were obvious. Unsuccessful (crash) landings increased from 2.3% (2/88) without GVS to 9% (7/88) with GVS. Hard landings, with touchdown speed in the 'red' (unacceptable) range (> 214 kn), almost doubled from 14 (15.9%) without GVS to 27 (30.7%) with GVS. **Conclusion:** GVS was an effective analogue of decrements in postflight Shuttle pilot performance.

Keywords: Shuttle, microgravity, reentry, space adaptation syndrome, vertical motion simulator.

PILOTS RETURNING from spaceflight are particularly prone to spatial disorientation (failure to correctly perceive the position, attitude, or motion of the spacecraft), as reflected in decrements in landing performance observed in the Shuttle program. A review of the first 100 missions found that 20% of Shuttle landings were outside of acceptable limits in terms of touchdown speed (19), the vast majority of which (19/20) were 'hot' (above target and potentially damaging to the landing gear). The maximum allowable touchdown speed of 217 kn [based on the main gear tire rating of 225 kn (23)] was equaled or exceeded on six occasions (19). The hardest touchdown on record (224 kn) has been linked to the commander's momentary loss of orientation ('tumbling the gyros') following an active head movement just prior to touchdown (19). The second hardest touchdown (220 kn) included a pilot induced oscillation (PIO) after main gear touchdown (19). An analysis of vertical velocity (sink rate) during actual Shuttle landings and preflight training in the Shuttle training aircraft (a modified Gulfstream II jet) from STS-43 to STS-108 demonstrated a higher variability postflight, with 10% of landings

above the target range of $3.5 \text{ ft} \cdot \text{s}^{-1}$ ($1.1 \text{ m} \cdot \text{s}^{-1}$) compared to 3% in preflight training (26).

The basis for postflight deficits in astronaut sensorimotor performance is not well understood, but may represent in-flight changes in central processing of afferent input coding linear acceleration. The peripheral vestibular apparatus of the inner ear consists of semicircular canals to sense angular head velocity and otolith organs that transduce linear acceleration. There is no physiological reason why semicircular canal function would be affected by microgravity and no changes have been noted in the yaw angular vestibulo-ocular reflex (VOR) (7). However, during head pitch and roll on Earth, otolith input encoding head tilt with regard to gravity is centrally integrated with angular canal information. Evidence that this amalgamation is disrupted in freefall and upon return to terrestrial gravity is seen in the reversal of up-down asymmetry in the gain of the vertical VOR (1,4), the vertical optokinetic response (17), and reduced roll VOR gain (4). There is considerable evidence that otolith-mediated responses are adversely affected by microgravity: asymmetrical ocular counter-rolling to leftward and rightward tilts both during in-flight centrifugation and after flight (16); deconditioning of otolith-spinal reflexes during simulated 'falls' (using elastic cords) in flight (29); post-landing postural instability with vision occluded (27); disruption of head stabilization in response to vertical translation of the trunk during postflight locomotion with concomitant oscillopsia (3); and a correlation between decrements in Shuttle landing performance (touchdown speed, vertical velocity, and height over runway threshold) and the severity of postflight postural instability in Shuttle commanders (5). In-flight changes in otolith symmetry, sensitivity, and central integration with canal input may render astronaut

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pilots prone to spatial disorientation in the hyper-gravity environment of landing; 80% of Shuttle crewmembers surveyed (11) reported that active head movements provoked illusory sensations of self- and surround-motion during reentry. Pilot performance may also be degraded by microgravity-induced changes in oculomotor (2,17), fine motor (30), and cognitive function (6). In addition to microgravity, crewmembers are exposed to a variety of stressors during spaceflight such as altered light-dark cycle, sleep deprivation, elevated CO₂ concentration, confinement, and high mental and physical workloads.

The 'gold standard' for replicating the physiological effects of spaceflight on Earth is head-down bed rest, where the subject lays on a bed tilted 6° head-down for periods of weeks to months (28). Bed rest is effective at simulating (at least qualitatively) the deconditioning effects of spaceflight on bone, muscle, and cardiovascular system function, but there are few data on whether sensorimotor performance is affected by the maintained re-orientation of the gravity vector. Our results from a 21-d study suggested that microgravity-induced decrements in sensorimotor function were not replicated by head-down bed rest; the amplitude and symmetry of ocular counter-rolling, and perception of the spatial vertical, were unchanged pre- and post-bed rest in response to 90° roll tilts to the left and right (20).

We have developed a technique to replicate the post-flight sensorimotor experience of astronauts by disrupting vestibular input in normal subjects by passing small electrical currents between mastoidal surface electrodes (bilateral bipolar galvanic vestibular stimulation - GVS). GVS acts at the spike trigger zone of primary vestibular afferents (10), activating predominantly irregular neurons from the otoliths and semicircular canals regardless of the directional preponderance of the hair cells they enervate. The net response signals roll angular velocity (with a small yaw component) and linear acceleration, both directed toward the cathode; consequently postural and oculomotor reflexes occur predominantly in the roll plane (9). CNS functions that integrate vestibular information with visual and somatosensory inputs (and which are not constrained to the roll plane), such as maintenance of antero-posterior (AP) stability during posturography (cerebellum) (14), obstacle course navigation (cerebellum/cortex) (18), and perception of motion (cortex) (24), are also degraded by bilateral bipolar GVS. The current waveform used in our GVS analogue, a pseudorandom sum of sines (14), was devised such that sensorimotor performance of normal subjects exposed to acute GVS replicated post-landing data from Shuttle and International Space Station (ISS) astronauts, namely AP postural sway (14) and locomotor impairment and decrements in dynamic visual acuity (18). Subjective validation was provided by seven veteran astronauts (five Shuttle, one ISS, one Skylab) who reported that the motor effects and illusory sensations of movement generated by the GVS analogue were remarkably similar to their post-landing experience (24). The ability of GVS to accurately replicate the postural, locomotor,

oculomotor, and perceptual difficulties experienced by astronauts suggests a primarily vestibular basis for these postflight sensorimotor deficits.

Ground-based simulations are frequently used in mission preparation. In the Shuttle program, for example, astronaut pilots train for landing in the vertical motion simulator (VMS) at NASA Ames Research Center and in the Shuttle training aircraft. These systems offer a high-fidelity reproduction of Shuttle handling abilities during final approach, but they do not replicate the effects of extended microgravity exposure on sensorimotor function, as evidenced by a comparison of the exceptional level of preflight performance with the postflight degradation observed in actual Shuttle landings (19,26). Future exploration class missions, such as to near-Earth asteroids or Mars, would entail docking and landing maneuvers to be performed (or supervised) following extended periods of weightlessness. The effectiveness of ground-based simulations in support of these missions would benefit from a realistic analogue of the effects of spaceflight on sensorimotor control. The aim of this study was to validate our GVS system as an appropriate analogue for future mission preparation by comparison of Shuttle landing performance in the VMS during galvanic stimulation with manual landing data after extended weightlessness from the Shuttle program. Our hypothesis was that touchdown speed and vertical velocity (sink rate) would be significantly higher during landing in the presence of GVS (relative to a no-GVS baseline), as observed in actual Shuttle landings following microgravity exposure (19,26).

METHODS

Subjects

There were 11 experienced professional pilots (all men) who participated in the experiment: 1 veteran astronaut (a former commander of 2 Shuttle flights, and a 3rd mission as pilot), 4 NASA test pilots, 5 veteran U.S. Air Force pilots, and 1 veteran U.S. Navy pilot. Seven of the participants had prior experience flying the VMS Shuttle landing simulation. A 12th potential recruit reported dizziness during initial exposure to GVS (within 10 s) and was excluded from participation in the study. All protocols were approved by the NASA Ames Human Research Institutional Review Board and the Institutional Review Board at Mount Sinai School of Medicine, and informed consent was obtained from all subjects.

Equipment

The VMS, used to simulate orbiter landings for astronaut pilot training, is one of the largest flight simulators in existence. A unique characteristic of the VMS is the range of linear motion; the motion base can translate up to 18.3 m vertically and 12.2 m horizontally, generating transient gravito-inertial acceleration magnitudes greater than 1 g. Operational motion limits (velocity and acceleration) are: 1.5 m · s⁻¹ 0.3-g longitudinal; 2.4 m · s⁻¹ 0.4-g lateral; 4.6 m · s⁻¹ 0.7-g vertical; 40° · s⁻¹/115° · s⁻²

roll; $40^\circ \cdot s^{-1}/115^\circ \cdot s^{-2}$ pitch; $46^\circ \cdot s^{-1}/115^\circ \cdot s^{-2}$ yaw. A dedicated Shuttle cabin is placed on a full-motion base and our experiment followed astronaut training in March and September 2009 to take advantage of the VMS Shuttle configuration. A rotational hand controller was positioned between the knees and the pilots placed their feet on the rudder pedals, which also operated the speed brake. As per nominal Shuttle operation, the speed brake was automated until touchdown, requiring no pedal input from the pilot during approach. After nose gear touchdown the rudder pedals were used for steering in yaw to maintain the Shuttle close to the centerline and toe deflection of the pedals provided braking during rollout. A head-up display (HUD) presented guidance and primary flight indicators (altitude, velocity, wind direction, etc.), as well as a prompt for the preflare maneuver at 2000 ft (610 m), a text indicator of potential navigational errors, and a graphical overlay of the runway. Continuous simulation data, including command inputs and Shuttle motion, were acquired at a rate of 25 Hz and stored for later analysis. Discrete touchdown metrics (speed and sink rate at touchdown, height above runway threshold) were also provided. The VMS system froze the simulation (vanity stop) when a crash was imminent to prevent potentially hazardous motion, which occurred 9 times in our experiment (5.1% of the 176 landings). In this instance computer projections of estimated speed and sink rate at touchdown were used.

Delivery of bilateral bipolar GVS was achieved using a constant-current generator that imposed a constant current amplitude independent of the load (subject) connected. This device consisted of a 9-V battery and a small box containing circuitry under computer control via a USB digital-to-analog converter (12-bit DA 1208LS, Measurement Computing, Middlesboro, MA). Current was delivered to the surface of the subject's skin via leads and large electrodes, cut from electrosurgical split grounding plate electrodes (7180, 3M Health Care, St. Paul, MN), placed over the mastoid processes. The electrodes were coated with an additional layer of EMG electrode gel, then applied to the surface of the subject's skin using the electrode's adhesive surround, and a piece of insulated tape was added to the skin underneath the bare metal tag. A soft pad was placed over each electrode and held firmly in place by an elasticized strap. The electrodes and strap did not produce discomfort or restrict head movement. The sum of sines current waveform, with dominant frequencies at 0.16, 0.33, 0.43, 0.61 Hz, and maximum current limited to ± 5 mA (14,18), activated the vestibular system in a push-pull manner, with the cathodal (excitation) and anodal (inhibition) electrodes switching sides with changes in current polarity. GVS generated small postural and oculomotor reflexes, entrained to the pseudorandom waveform, predominantly in the roll plane (14,18). Subjectively, these reflex responses gave one the feeling that the ground was not stable, but was rocking slightly from side to side in a random manner, as if on a boat in rough waters.

Procedure

After informed consent pilot participants were briefed by VMS staff. During Shuttle landing the pilot (in actual missions this is the Shuttle commander) assumes manual control upon entering subsonic flight (Mach 0.95; 628 kn) and at an altitude of 40,000 ft (12,192 m) banks the Shuttle around a virtual cylinder (radius 5500 m) to line up with the runway. At this point the Shuttle is approximately 12 km from the runway at an altitude of 10,000 ft (3028 m) traveling at 295 kn, which was the initial condition for the simulations in the current study. From this point the orbiter is on final approach (Fig. 1). The vehicle descends on a 20° glide slope and at an altitude of 2000 ft (610 m) the commander brings the Shuttle nose up with a pitch command (preflare), presenting a larger surface area to the oncoming airflow and slowing the vehicle while transitioning from the steep (20°) outer glide slope to the shallow (1.5°) inner glide slope in preparation for touchdown. The landing gear is deployed at 300 ft (91 m) and a final flare (pitch) maneuver slows the vertical velocity (sink rate, or Hdot) to $3.5 \text{ ft} \cdot s^{-1}$ ($1.1 \text{ m} \cdot s^{-1}$), and touchdown occurs at a nominal speed of 204 kn for heavy ($> 100,000 \text{ kg}$) vehicles (23). A drogue chute is deployed after main gear touchdown. The commander controls drift with the rudder pedals and applies the speed brake until the orbiter comes to a stop.

Subjects had up to 2 h to practice landings using five profiles similar to those from the actual experiment until demonstrating competence as defined by acceptable values on three landing parameters used to monitor performance in astronaut training: touchdown speed (target 204 kn; acceptable < 214 kn), sink rate or Hdot (target $< 3.5 \text{ ft} \cdot s^{-1}$; acceptable $< 5 \text{ ft} \cdot s^{-1}$), and height at runway threshold (target 26 ft; acceptable < 40 ft). All subjects were proficient with less than 1 h of training.

Subjects were instrumented with the GVS electrodes and performed a posturography task using a Wii Balance Board (Nintendo, Kyoto, Japan). We have previously validated the use of the Wii platform by direct comparison of sway measures with commercially available force plates (MacDougall HG, Burgess AM, Halmagyi GM, Curthoys IS. A portable and affordable vestibular testing kit. The Garnett Passe and Rodney Williams Memorial Foundation - Frontiers in Otorhinolaryngology;

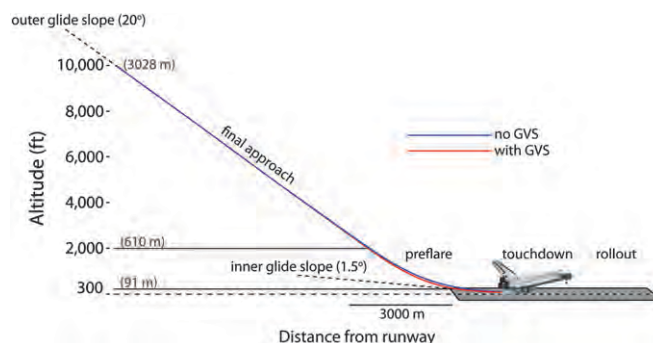


Fig. 1. Shuttle altitude versus distance from runway (mean of 88 landings) with (red trace) and without (blue trace) GVS.

Noosa, Australia; 2008). Subjects stood on the platform with feet together and eyes closed without Galvanic current as movement of the center of pressure (COP) was acquired for 20 s at a sample rate of 100 Hz. After a brief interlude the task was repeated with GVS.

Following posturography pilot participants were seated in the VMS Shuttle cockpit in the left (commander's) seat. Two investigators accompanied the subject during testing; one sat in the right (pilot's) seat and deployed the drogue chute after touchdown, and the other sat in the jump seat and operated the GVS system. Subjects performed 8 pairs of identical landing profiles (final approach and touchdown; Fig. 1) with and without GVS, presented in a pseudorandom order (16 landings per subject; 176 total; 88 with and 88 without GVS). Initial conditions were a landing weight of 226,242 lb (102,622 kg), 9910 ft (3021 m) altitude, and 295 kn airspeed; target touchdown speed was 204 kn with a vertical sink rate of less than 3.5 ft · s⁻¹ (1.1 m · s⁻¹). Each landing took approximately 100 s, thus subjects were exposed to an average of 13 min of GVS during the experiment. The landing profiles were taken from the training matrix for astronaut pilots with ceiling variations, surface winds, navigational offsets, and HUD failures based on actual Shuttle landings (Table I). As per standard operating procedure, pilots were informed of the ceiling, visibility, and surface winds at the start of each run by the simulation engineer. Subjects were alerted to potential navigational errors soon after the simulation began via text on the HUD indicating the severity (and source) of the anomaly: figure of merit (FOM; Microwave Scan Beam Landing System) 4A (Table I; run 1); FOM 4B (Table I; run 2); tactical air navigation (TACAN) 3 (Table I; run 5); and TACAN 1 (Table I; run 6).

Statistical Analysis

Shuttle altitude and vertical velocity are measured in U.S. customary units of feet (ft) and feet per second (ft · s⁻¹). We have reported these parameters in their conventional units in the text, with the SI equivalents added to the figure plots. Airspeed is reported in knots (kn) and distance from the runway in SI units. Variance is stated as the 95% confidence interval of the mean and statistical testing was carried out with repeated measures

ANOVA (results considered significant for *P* < 0.05). Linear regression (least-squares method) was used to determine potential correlations between parameters, reported as Pearson's *r* and significance (*P*).

RESULTS

The Shuttle approach was similar with and without GVS, with the exception of a small but significant tendency to fly lower during preflare with GVS (Fig. 1). At a distance of 2000 m from the runway, altitude (mean and 95% CI of 88 landings) was 475.4 ft (CI 110.6) without GVS and 385.7 ft (CI 89.1) with GVS, a difference of 89.7 ft (*P* = 0.0002). Upon reaching the runway threshold, however, the altitude differential (5 ft) was negligible [no GVS 32.7 ft (CI 3.2); with GVS 27.7 ft (CI 3.9); *P* = 0.1]. Touchdown speed increased significantly (*P* = 0.02) with GVS relative to the no-GVS condition, from 203.8 kn (CI 3.3) to 208.5 kn (CI 4.6). Although representing an average increase of only 4.7 kn, GVS application pushed mean touchdown speed from on-target at 204 kn to the upper limit of the target range (209 kn; Fig. 2A). Mean sink rate tended to increase with GVS from 3.8 ft · s⁻¹ (CI 0.5) to 4.3 ft · s⁻¹ (CI 0.7) (Fig. 2B), although not significantly so (*P* = 0.08). The adverse effects of GVS on pilot performance were obvious (Fig. 2C). Unsuccessful (crash) landings increased from 2.3% (2/88) without GVS to 9% (7/88) with GVS. Hot landings, with touchdown speed in the 'red' (unacceptable) range (> 214 kn), almost doubled from 14 (15.9%) without GVS to 27 (30.7%) with GVS; GVS also induced a 32% increase in the number of landings with a sink rate in the unacceptable range (> 5 ft · s⁻¹), from 19 to 26.

Command input and Shuttle motion during preflare from identical landing profiles, with and without GVS (Table I; run 1), flown by the veteran Shuttle commander are shown in Fig. 3. Run 1 was the most straightforward profile used in the experiment, with minimal wind, a small navigation offset, and a functional HUD. Preflare was delayed (and therefore slightly lower) with GVS (Fig. 3A; Fig. 1). Roll (Fig. 3B) and pitch (Fig. 3D) commands from the pilot, and subsequent Shuttle motion, were smooth without GVS, as expected for a profile with minimal wind. When exposed to GVS, large roll inputs were induced (Fig. 3C), likely due to the pilot perceiving

TABLE I. THE EIGHT LANDING PROFILES USED IN THE EXPERIMENT ADAPTED FROM THE TRAINING MATRIX FOR ASTRONAUT PILOTS.

Run	Ceiling [ft (m)]	Visibility [miles (km)]	Surface winds (kn)	Navigation offset [ft (m)]			Hdot offset [ft · s ⁻¹ (m · s ⁻¹)]	Airfield	HUD
				vertical	lateral	range			
1	8000 (2438)	7 (11.3)	0.9T 4L	+90 (27.4)	+240 (73.2)	+150 (45.7)	3 (0.9) down	KSC	YES
2	10,000 (3048)	7 (11.3)	1H 4L	+90 (27.4)	-240 (73.2)	+150 (45.7)	1 (0.3) up	EDW	YES
3	10,000 (3048)	5 (8)	24H 10R	0	0	0	0	KSC	YES
4	8000 (2438)	7 (11.3)	15T 13L	0	0	0	0	EDW	YES
5	8000 (2438)	5 (8)	6T 4R	0	+1200 (365.8)	+400 (121.9)	2 (0.6) down	KSC	YES
6	8000 (2438)	5 (8)	6T 12L	0	-1200 (365.8)	-400 (121.9)	2 (0.6) up	EDW	YES
7	10,000 (3048)	5 (8)	6H 12R	0	0	0	0	KSC	NO
8	8000 (2438)	7 (11.3)	4H 6R	0	0	0	0	EDW	NO

Abbreviations: T - tail wind; L - left wind; R - right wind; H - head wind; KSC - Kennedy Space Center; EDW - Edwards Air Force base; HUD - Head-up display; Hdot - vertical velocity (sink rate).

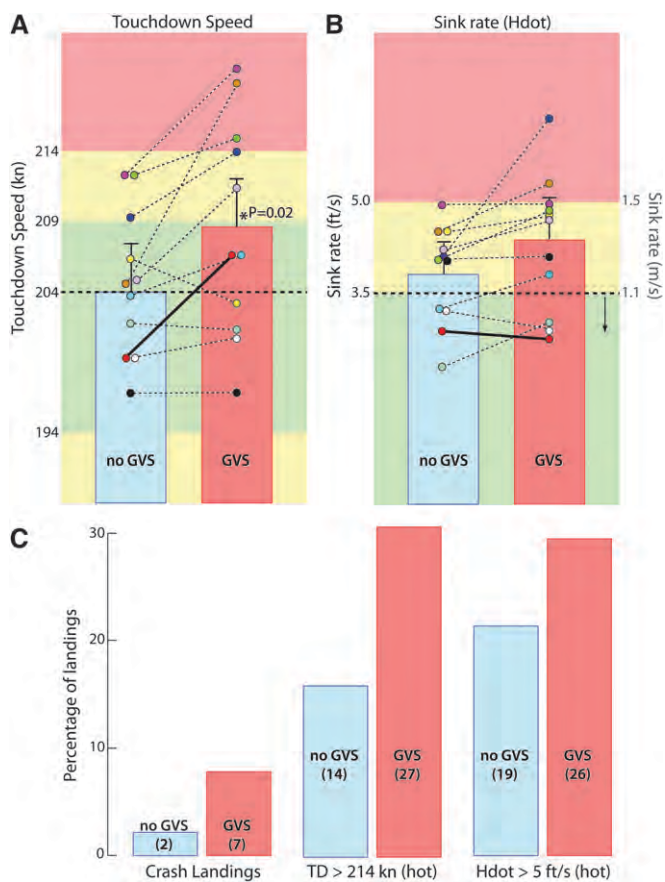


Fig. 2. A) Touchdown speed (mean and 95% CI) with (red column) and without (blue column) GVS. The green region indicates target touchdown speed (194–209 kn), the yellow region is ‘acceptable’ (< 194 kn; 209–214 kn), and the red region is ‘unacceptable’ touchdown speed (> 214 kn). Colored circles and dashed lines indicate individual means; red circles with thick line denote the most experienced subject, a veteran Shuttle commander. B) Sink rate (mean and 95% CI) with (red column) and without (blue column) GVS. The green region indicates target sink rate (< 3.5 ft · s⁻¹), the yellow region is ‘acceptable’ (3.5–5 ft · s⁻¹), and the red region is ‘unacceptable’ (> 5 ft · s⁻¹). C) Percentage of crash landings, hot landings (touchdown speed > 214 kn), and sink rate during landings > 5 ft · s⁻¹ with and without GVS.

the pseudorandom Galvanic current as roll perturbations of the Shuttle. However, the effects of GVS were not confined to roll; erroneous pitch commands, including a pilot-induced oscillation, were also observed (Fig. 3E; PIO).

The adverse effects of GVS on pilot performance during preflare were consistent across all subjects (Table II). Roll and pitch command and Shuttle motion data from all 176 landings were split into 3 bins based on altitude: approach (> 2000 ft), preflare (2000–300 ft), and touchdown (< 300 ft), and the root mean square (RMS) and peak-to-peak (P-P) values calculated. With the exception of a paradoxical 17.6% decrease in RMS roll rate of the Shuttle during touchdown, the only segment of the landing in which roll and pitch control was significantly affected by GVS was preflare (Table II). Both RMS (9.3%) and P-P (9.8%) roll command increased with GVS during preflare, and roll rate of the Shuttle increased by 25% (RMS) and 13.4% (P-P). GVS induced increases in the pitch command input of 13.0% (RMS) and 26.7% (P-P),

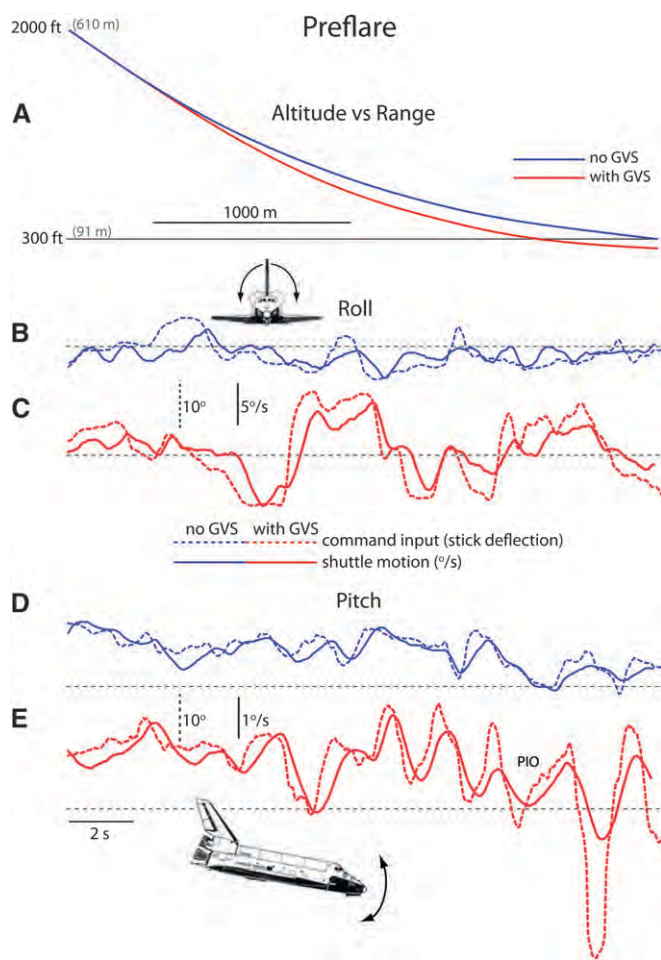


Fig. 3. Command input (stick deflection) and Shuttle motion data (angular velocity) during preflare for identical landing profiles (run 1 – see Table I) with (red traces) and without (blue traces) GVS; the subject was a veteran Shuttle commander of three missions. A) Altitude versus range. B) Roll input (blue dashed line) and Shuttle roll motion (blue solid line) without GVS. C) Roll input (red dashed line) and Shuttle roll motion (red solid line) with GVS. D) Pitch input (blue dashed line) and Shuttle pitch motion (blue solid line) without GVS. E) Pitch input (red dashed line) and Shuttle pitch motion (red solid line) during GVS. PIO - pilot-induced oscillation.

and Shuttle pitch velocity increased 20% (RMS) and 21% (P-P).

Mean COP movement increased significantly with GVS during the preflight posturography task. AP range of COP translation (Fig. 4A) increased from 3.1 mm (CI 0.39) without GVS to 9.0 mm (CI 3.0) with GVS ($P = 0.0006$); medio-lateral (ML) range was 3.2 mm (CI 0.43) without and 14.8 mm (CI 5.3) with GVS ($P = 0.0003$); total path length of the COP was 67.1 mm (CI 13.1) without and 217.2 mm (CI 77.7) with GVS ($P = 0.001$). As previously reported (15), there was considerable inter-subject variability in the response to GVS (Fig. 4A). The difference in COP range with and without GVS in the AP and ML directions, and path length positively correlated with the difference in mean touchdown speed with and without GVS for each subject (Fig. 4B; $N = 10$; one subject was excluded from the regression analyses as an outlier as Δ touchdown speed was > 2.5 SD above

TABLE II. ROOT MEAN SQUARE (RMS) AND PEAK-TO-PEAK (P-P) VALUES FOR PILOT COMMAND INPUT AND RESULTANT SHUTTLE MOTION IN PITCH AND ROLL DURING THE THREE PHASES OF LANDING.

		Final Approach			Preflare			Touchdown		
		No GVS	GVS	P	No GVS	GVS	P	No GVS	GVS	P
Roll command (°)	RMS	4.4	4.5	0.80	4.3	4.7	0.04*	3.1	3.1	0.94
	P-P	21.4	21.8	0.65	17.4	19.1	0.04*	23.1	24.8	0.06
Roll rate (° · s ⁻¹)	RMS	1.4	1.5	0.48	1.2	1.5	0.01*	0.9	0.9	0.58
	P-P	9.5	10.0	0.46	6.7	7.6	0.04*	11.3	12.0	0.31
Pitch command (°)	RMS	2.4	2.5	0.07	5.4	6.1	< 0.001*	3.4	2.8	0.03*
	P-P	14.4	15.1	0.21	10.1	12.8	< 0.001*	22.5	22.6	0.96
Pitch rate (° · s ⁻¹)	RMS	0.3	0.4	0.05	1.0	1.2	< 0.001*	0.8	0.7	0.05
	P-P	2.4	2.6	0.05	2.4	2.9	< 0.001*	7.6	7.6	0.91

The three phases of landing were: final approach (10,000–2000 ft; 3048–610 m); preflare (2000–300 ft; 610–91 m); and touchdown (< 300 ft; < 91 m)
 * Significant changes relative to no GVS condition.

the group mean). That is, the change in the AP ($r = 0.75$, $P = 0.01$) and ML ($r = 0.69$, $P = 0.03$) extent of COP translation, and the path length ($r = 0.75$, $P = 0.01$) during GVS exposure were predictors of the effect of GVS on pilot landing performance with regard to touchdown speed. The change in postural sway during GVS was not correlated with the sink rate or height at runway threshold deltas.

DISCUSSION

The main finding of this study was that application of a pseudorandom Galvanic current stimulus during

high-fidelity simulated Shuttle landings induced decrements in pilot performance consistent with that observed after microgravity exposure in the NASA Shuttle program (19). In particular, mean touchdown speed increased by almost 5 kn and was at the upper limit of the targeted speed range, and the number of ‘hot’ landings (touchdown speed > 214 kn) increased by 93%. Mean sink rate at touchdown was not significantly affected by GVS, but the number of landings with a sink rate in the unacceptable range (> 5 ft · s⁻¹; 1.5 m · s⁻¹) increased by 32% during GVS exposure. Galvanic stimulation significantly increased roll and pitch command input and resultant motion of the Shuttle, but only during the preflare

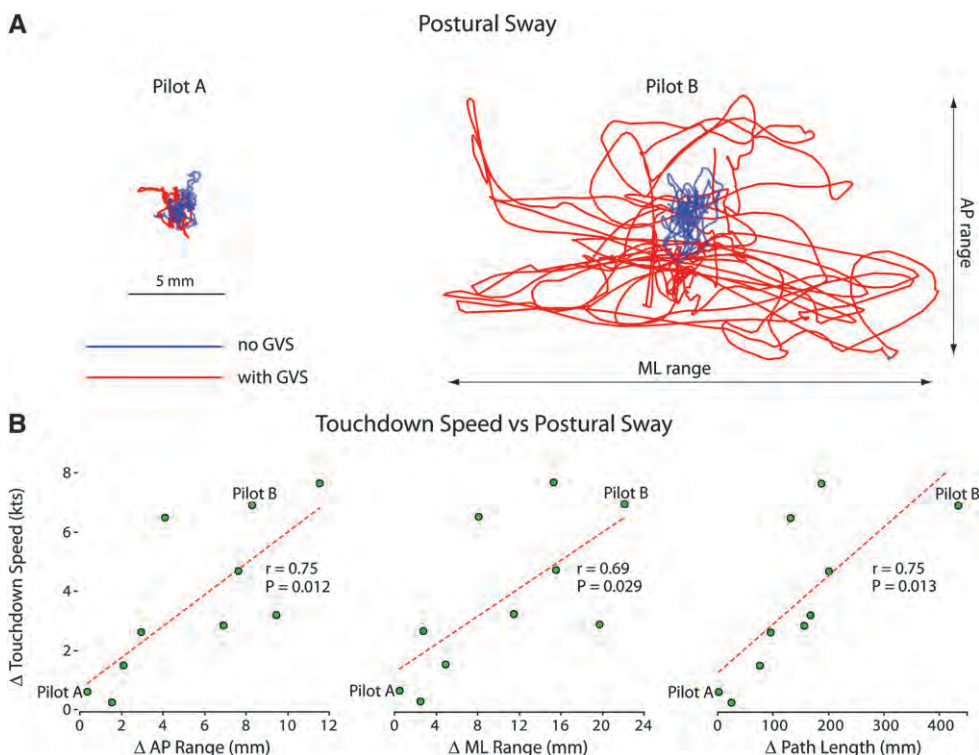


Fig. 4. A) Sway data (center of pressure - COP) during posturography with (red trace) and without (blue trace) GVS from two subjects (denoted ‘Pilot A’ and ‘Pilot B’). B) Individual change in mean touchdown speed with and without GVS (Δ touchdown speed) versus (from left to right) Δ COP AP sway range (individual change in mean AP range with and without GVS), Δ COP ML sway range, and Δ COP path length.

maneuver. Mean altitude was significantly lower with GVS during preflare, but there was no difference in Shuttle height at the runway threshold.

The observed decrements in pilot performance with GVS may have been due to a number of factors, including degradation of vestibular afferent input to the central nervous system (CNS), reduced visual acuity from reflexive eye movements, or adverse cognitive effects. Bilateral bipolar GVS was unlikely to have significantly affected visual acuity as the reflex eye movements occur mostly in roll (15) [foveal acuity is relatively independent of rotation about the line of sight (12)], and we have recently demonstrated that the GVS analogue (like microgravity exposure) does not affect attentional cognitive function (8). The increase in individual postural sway induced by GVS was strongly correlated with the change in touchdown speed magnitude with GVS exposure for each pilot, which suggests the degradation in landing performance was primarily due to the vestibular effects of Galvanic stimulation. We hypothesize that the afferent vestibular signal was modulated by the sum-of-sines current waveform at the spike trigger zone of the vestibular nerve, resulting in small reflex responses in the roll plane (14) and distortion of vestibular input to higher-level functions of the CNS (14,18). Central programs that rely on veridical vestibular input to compute spatial orientation would be compromised, as was likely the case for returning Shuttle astronauts adapted to the relative lack of gravity in flight. Galvanic vestibular stimulation was an effective analogue for the detrimental effects of microgravity exposure on piloting performance, even though the underlying physiological mechanisms of spatial disorientation due to spaceflight (adaptation to lack of a gravitational vector in flight) and GVS (electrical stimulation of the vestibular nerve) are likely very different.

The most critical phase of Shuttle landing is preflare. Proper command input depends on accurate spatial orientation, and the resultant flare maneuver determines landing metrics such as touchdown and sink rate (26). With the orbiter only a few hundred meters above the ground, the transition from the outer (20°) to inner (1.5°) glide slope, accomplished with a deflection of the control stick toward the pilot that pitches the Shuttle nose-up, generates a transient 1.4-g spike in gravito-inertial acceleration along the long-body axis (19). This is likely an intense stimulus for astronaut pilots adapted to the relative absence of gravity on orbit. Preflare also requires central integration of dynamic angular (semicircular canal) and linear (otolith) input, which is adversely affected by microgravity exposure. In the current study, application of GVS did not result in a blanket impairment of pilot control, inducing significant changes in roll and pitch command input only during the preflare maneuver. Under optimal conditions (eyes open, stable support surface) the effects of GVS (14) and microgravity (27) on motor function are mild, as other sensory modalities (particularly vision) can provide adequate veridical information to maintain proper function. However, if the CNS is challenged, such as during

preflare (or closing the eyes with a narrow base of support), the adverse effects of GVS (14) and spaceflight (19,26,27) are significant.

With the end of the Shuttle era it is likely that future mission scenarios will rely less on manually piloted landing and docking maneuvers. However, there is a compelling argument for maintenance of operator proficiency during and after spaceflight, even during automated tasks. In-flight failures of automatic control requiring corrective action from the crew have occurred in both the Russian and U.S. space programs: automated guidance of Voskhod 2 (1965) failed prior to reentry and the crew manually positioned the spacecraft for reentry, selected the landing point, and determined the correct timing and duration of the deorbit burn (13,25); manual retro-fire was carried out on Soyuz 1 (1967) after on-orbit failure of the attitude control system (25); the crew of Gemini VIII (1966) disabled the attitude control system and engaged the reentry control system to recover from a 'stuck' thruster (22); and, following an oxygen tank explosion in the service module of Apollo XIII (1970), the crew regained control of the spacecraft using the lunar module thrusters (21) and performed manually controlled burns with the lunar module descent engine (a contingency they had not trained for) to position the spacecraft for a successful return to Earth. In these cases the crew were supported by ground-based mission control. In future missions to distant objects such as Mars the ability of mission control to communicate directly with the crew will be hampered by the time of transmission (up to 20 min one way Earth to Mars) and, during critical phases of spacecraft operation, the crew will essentially be working in isolation. Moreover, current experience with ISS astronauts suggests that sensorimotor performance will be compromised following a 200-d transit (based on existing spacecraft technology) to Mars. Preparation for future long-duration missions would benefit from augmenting high-fidelity simulations with an analogue of the effects of microgravity on sensorimotor control. We have demonstrated that our GVS analogue accurately replicates the adverse effects of spaceflight on balance (14), gait (18), dynamic visual acuity (18), and, with the results of the current study, pilot performance. The Galvanic stimulus is well-tolerated (8), available at the 'flick of a switch', reversible [sensorimotor function returns to baseline within minutes of terminating exposure (14)], and the GVS system is ambulatory, allowing its use in a wide range of operational environments.

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