Head-Eye Coordination During Simulated Orbiter Landing


Background: Orbiter landing data show decrements in pilot performance following spaceflight compared to preflight simulated landings. This study aimed to characterize pilot head-eye coordination during simulated orbiter landings, and relate findings to microgravity-related spatial disorientation. Methods: Orbiter landings were simulated in an A340-300 simulator flown by six pilots. Turns about the Heading Alignment Circle (HAC) to align the orbiter with the runway were simulated by 45° banking turns. Final approach was simulated with an 11° glide slope from an altitude of 4267 m, with preflare at 610 m and touchdown at 200 kn. Orbiter landings were also performed in the Vertical Motion Simulator (VMS) at NASA Ames by a NASA test pilot. Results: A340: During the HAC maneuver the head and eyes rolled toward the visual horizon with a combined gain of 0.14 of bank angle. Pilots alternated fixation between the instruments and the runway during final approach, almost exclusively focusing on the runway after preflare. Optokinetic nystagmus was observed during rollout. VMS: Head and eye roll tilt when rounding the HAC were of similar magnitude to that observed in the A340. During final approach the Heads-Up Display (HUD) reduced pitch head and eye movement. Conclusions: Roll tilt of the head and eyes during the HAC tended to align the retina with the visual horizon. Overlaying critical flight information and the approaching runway with the HUD reduced pitch head and eye movement during orbiter final approach in the VMS relative to the A340 (no HUD installed). Keywords: shuttle, microgravity, reentry, spatial disorientation, space adaptation syndrome.

Reentry and landing of the shuttle imposes unique inertial demands upon astronaut pilots adapted to the virtual absence of gravity during orbital flight. Hypergravity is experienced at three critical stages (Fig. 1A and B). 1) Upon entering the atmosphere [entry interface at 121,920 m (400,000 ft)], there is an increasing deceleration due to atmospheric drag that peaks at 1.5 g; 2) after the commander assumes manual control (at a speed of Mach 0.95) and banks the orbiter [beginning at an altitude of 12,192 m (40,000 ft)] about the Heading Alignment Circle (HAC—a virtual cylinder of 5500 m radius generated by the Microwave Scan Beam Landing System) to align with the runway for final approach, generating a 1.2-g gravito-inertial acceleration (GIA) vector (the sum of all linear acceleration acting on the head, including gravity; when banking the GIA reflects combined centripetal and gravitational acceleration, and is aligned with the cockpit vertical); and 3) during preflare [610 m (2000 ft)] to transition the orbiter from a steep (18–20°) to shallow (1.5°) glide slope in preparation for landing, producing a transient 1.4-g linear acceleration spike along the cockpit vertical.

Pilots returning from spaceflight are particularly prone to spatial disorientation, a failure to correctly perceive the position, attitude, or motion (5) of the spacecraft. A survey of crewmembers on short- and medium-duration shuttle missions reported that illusions of self-and/or surround-motion during active head movements occurred in 70–80% of subjects during reentry and 90–100% at wheels stop (14). The most common illusions were a sense of exaggerated head movements, persistence of visual surround movement, and illusions of path, such as an angular head motion generating a sense of translation.

The basis for postflight deficits in sensorimotor function is not well understood, but likely represents changes in central processing of low-frequency otolith afferent input (located in each inner ear, the otoliths respond to combined linear acceleration acting on the head) in microgravity that persists into the postflight period, and affects postural, locomotor, oculomotor, and perceptual function (8,21–23). There is evidence that the otolith-mediated ocular counter rolling (OCR) reflex (rotation of the eye about the line of sight during lateral head tilt) is reduced 30–50% in the majority of astronauts tested following spaceflight (22). An asymmetry in OCR to leftward and rightward tilts has been observed both during (22) and after flight (22,33), possibly due to unmasking of an inherent asymmetry in afferent otolith information during prolonged microgravity exposure (32). Changes
in otolith sensitivity and symmetry may render astronaut pilots prone to acceleration-dependent disorientation in a hypergravity environment, such as the g-excess effect [in which tilts of the head feel exaggerated (13)] during the HAC maneuver and the somatogravic illusion [erroneous sensations of spacecraft pitch (8,9)] throughout preflare, touchdown, and rollout. In addition, in-flight studies have suggested that adaptation to microgravity involves a decrease in the magnitude of the internal body vertical (idiotropic) vector, leading to exaggerated postflight sensations of roll and pitch tilt in the presence of interaural or naso-occipital head acceleration (8). Arguably the most dangerous phase of orbiter landing is from preflare to touchdown (see description of ‘flight A’ below); with the orbiter only 610 m above the ground the transient 1.4-g spike during preflare is likely an intense stimulus for pilots with a vestibular system that has adapted to microgravity in a manner unsuited for operation in terrestrial gravity.

There have been a number of instances where spatial disorientation is believed to have adversely affected landing of the orbiter. The hardest touchdown on record (224 kn) occurred in the late 1990s (Fig. 2; ‘flight A’), and has been putatively linked to the commander’s momentary loss of orientation (“tumbling the gyros”) following an active head movement just after preflare and prior to touchdown (7). A second event, which occurred near the beginning of the shuttle era (early 1980s) and perhaps not coincidentally was the second hardest touchdown at 220 kn (Fig. 2; ‘flight B’), seemingly involved the somatogravic illusion (8,9). During the landing of ‘flight B’ (after the orbiter’s main gear had touched down but the nose wheel was still off the ground), the pilot, presumably sensing the backward pitch of the GIA produced by deceleration as a

Fig. 1. A) Linear acceleration experienced during orbiter landing (STS-41). B) The final 7 min of an orbiter landing: a-b) the commander assumes manual control (CSS-control stick steering); c-e) the orbiter is banked around the HAC to align with the runway for final approach; e-f) the orbiter descends on an 18–20° glide slope; f) preflare transitions the orbiter to a 1.5° inner glide slope; g) touchdown occurs at a nominal speed of 195 kn for lightweight orbiters [less than 100 t (15)] and 204 kn for heavy vehicles (25).
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Fig. 2. Orbiter touchdown speed for the first 100 missions (17). Light gray shaded regions depict the desired range of target touchdown speeds, dark gray regions are ‘acceptable’ (adapted from target landing speeds of 194 kn for ‘light’ and 204 kn for ‘heavy’ orbiters, and allowable deviations from target touchdown speeds used in astronaut pilot training in the VMS).

A rapid nose-down tilt, pulled back on the control stick, inducing a dangerous pitch oscillation of the spacecraft.

A study of nine shuttle missions found that decrements in landing performance (height over threshold, vertical velocity, and touchdown speed) correlated with the severity of postflight neurological symptoms, particularly dynamic disequilibrium and sensorimotor deficits (19). Touchdown speed is a particularly critical parameter. NASA has set an upper limit of 217 kn due to the risk of tire failure during landing (main tires are rated at 225 kn maximum) (17,25). Touchdown speeds for the first 100 missions (17) demonstrated a large variability (Fig. 2) in contrast to pilot performance during numerous preflight simulated landings in the Vertical Motion Simulator (VMS) at NASA Ames and the Shuttle Training Aircraft (7). Of orbiter landings, 20% were outside of acceptable limits (Fig. 2), and the maximum speed of 217 kn has been equaled or exceeded on six occasions (including flights ‘A’ and ‘B’ described above).

The aim of this study was to characterize head-eye coordination of pilots during simulated orbiter landings and relate these findings to the potential for spatial disorientation. A number of studies have investigated visual scanning patterns of pilots during simulated flight (2-4,27,31), focusing primarily on fixation and dwell times for various instrument displays; the gaze response to disorientating head roll motion has also been quantified (4). However, these studies did not measure head movement. During banking a visually dependent reflexive tilt of the head, the ‘optokinetic cervical reflex’ (OKCR), has been described (1,11,12,28,30). The OKCR tilts the head in roll toward alignment with the spatial (Earth) vertical (in the direction opposite to the aircraft bank angle) when the pilot is looking outside the cockpit window. During orbiter landing there is a large sustained banking turn (the HAC maneuver) that dissipates energy and aligns the spacecraft with the runway for final approach (Fig. 1B). We hypothesized that the OKCR would be prominent during this phase. No previous studies of pilot performance have used an integrative approach accounting for both eye and head movement, and in the current study we used a novel measurement technique (18) to quantify 3D movement of the head, eyes, and cabin during simulated landing of the orbiter. Due to limited access to the shuttle landing simulator (VMS) at NASA Ames, our approach was to model orbiter landing using a commercial full-motion flight simulator (Airbus A340-300). For comparison we present a case report from a NASA test pilot, experienced in simulated shuttle landings, during high-fidelity orbiter landing simulations in the VMS.

METHODS

All protocols were approved by the Institutional Review Board at Mount Sinai School of Medicine and informed consent was obtained from all subjects. Experiments conducted at NASA Ames Research Center were additionally approved by the NASA Human Research Institutional Review Board.

Subjects

Six experienced pilots (5 men; 1 woman), drawn from Airbus personnel, flew an A340-300 Level-D full-motion simulator at the Airbus training facility in Toulouse, France. The subject pool consisted of four test pilots (one of whom was a veteran European Space Agency astronaut/pilot), one training supervisor, and one line pilot. A male NASA test pilot, experienced in simulated orbiter landings, was recruited to fly the VMS at NASA Ames Research Center.

Measurement Equipment

Head and eye movements were acquired at a sample rate of 30 Hz using a custom video-oculography system (see 18 for a detailed description). Two ‘firewire’ (IEEE 1394) digital cameras (Firefly, Point Gray Research, BC, Canada) were attached to either side of lightweight (130 g) swimming goggles (Aquasphere Seal, Genova, Italy). The left eye was illuminated by an IR light emitting diode (HSDL-4220, Hewlett-Packard, Houston, TX), and the image of the eye was directed onto the left camera via a dichroic mirror that reflected light in the IR band but allowed visible light to pass through, providing a clear field of view for the subject (116° horizontal; 62° vertical). The right camera was directed forward (parallel to the naso-occipital axis), providing images of the scene from the pilots’ point of view. Head movement (3D linear acceleration, angular velocity, and angular position) was measured with a miniature inertial measurement unit (MT9, Xsens, Enschede, The Netherlands) weighing 32 g and attached to the head by a lightweight plastic headband (18). A second inertial measurement unit measured movement of the cockpit. All video and movement data were logged onto a PC laptop computer. In the A340-300 simulator the copilot’s Primary Flight
Display (PFD) was recorded with a digital video camera mounted to a small fold-down tray table in front of the instrument panel. Sound cues (two beeps at the start of data acquisition and one at the end) were recorded onto the PFD video soundtrack. Simultaneously, these cues were saved as event markers within the data files on the laptop. This allowed pilots' head and eye movement data to be synchronized with the PFD video post hoc. Data from the orbiter's instruments were provided by the VMS control system.

Horizontal and vertical eye movements were calibrated prior to testing by having the subject view targets generated by a goggle-mounted laser (Class 3A < 5 mW 635 nm visible laser diode module) with a diffraction grating (Laser X-Hair Generating Optic, Lasermate Group Inc., Pomona, CA). The laser projected a cross pattern of lines fixed with respect to the head that subtended a visual angle of ± 9° horizontally and vertically. The laser display was also visible in the scene image to calibrate point-of-regard (i.e., where the pilot was fixating within the scene video). Horizontal and vertical eye movements (in head coordinates) were calculated by tracking the center of the pupil (18,24). Torsional (roll) eye position was calculated using polar cross-correlation, where pixels within the iris are sampled using elliptical annuli centered on the pupil and cross-correlation of these signals provides the amount of relative rotation about the line of sight between two images. These algorithms have demonstrated an accuracy and resolution of the order of 0.1° (24). The bank angle of the aircraft (A340-300) was calculated from the PFD video by tracking the aircraft roll indicator (using digital image processing). Airspeed was manually determined from the video recordings. The falling edge of the sound pulse on the PFD video, recorded during testing, was used to synchronize the PFD bank angle data and airspeed with the eye movement traces and scene video to within 16 ms. According to the right hand rule, a clockwise (CW) roll of the aircraft, eye, or head (from the pilots' point of view) was positive. Yaw head and eye movements were positive left, and pitch rotations positive down (note that pitch head and eye movement traces have been inverted in the figures to facilitate interpretation).

Experimental Paradigm I: The HAC Maneuver

The HAC maneuver was simulated in the A340-300 by having pilots perform a series of large (~45°) banking turns using the visual (Earth) horizon as a guide (Fig. 3) while maintaining a constant simulated altitude of 4267 m (14,000 ft)—the altitude at which the orbiter exits the HAC) and an indicated airspeed of between 260–280 kn. Weather conditions were set to fine and visibility was 100%. For one subject zero visibility conditions (clouds) were also simulated to assess the effect of vision on roll head and eye movements (Fig. 3E). The A340-300 simulator was run in fixed-base mode with no movement of the cabin during banking maneuvers. Note that even in full-motion mode, banking is simulated with the cabin upright, with only small (~2°) transient roll motion when initiating turns.

The pervasive sense of aircraft bank is generated almost exclusively by the visual display of a tilted horizon outside the cockpit window. Subjects initially banked to the right (a CW roll of the aircraft from the pilots' point of view). No instruction was given as to the angular velocity of the bank, but subjects were asked to hold the turn for a period of approximately 15 s after reaching the desired bank angle of 45°, then roll the aircraft to the left (counterclockwise; CCW) to a bank angle of approximately −45°, again holding for around 15 s. This sequence was repeated four times for a total of eight turns per subject.

Experimental Paradigm II: Final Approach and Landing A340-300

For this experiment the A340-300 simulator was run in full-motion mode. A landing profile was developed (see Fig. 4) that matched the orbiter final approach and landing as closely as A340 flight characteristics allowed. Pilots flew a simulated steep (~11°) outer glide slope (Fig. 1B; e-f), starting from an altitude of 4267 m (14,000 ft), 28.5 km (15.4 nautical miles) from the runway at an airspeed of 250 kn. Turbulence was set at 25% (mild) and visibility was 100%. At an altitude of 610 m (2000 ft) a preflare maneuver was performed to bring the aircraft onto a final (inner) 1.5° glide slope, with a target touchdown speed of 200 kn. During rollout the throttle was reduced to zero, but reverse thrust was not engaged. The landing gear was deployed during the steep descent to increase drag, then retracted at 914 m (3000 ft), and redeployed at 91 m (300 ft), analogous to the orbiter. The major difference between the modified A340 and orbiter landing profiles was the outer glide slope; the maximum possible for the A340 was 11°, four times steeper than a commercial airline approach, and a little more than half the angle of the orbiter (18–20°).

Experimental Paradigm III: Orbiter Landings (VMS)

The VMS, used to simulate orbiter landings for astronaut pilot training, is one of the largest and most complex flight simulators in existence. A dedicated shuttle cabin is placed on a full-motion base. 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 GIA magnitudes greater than 1 g (as, for example, during the preflare maneuver—see Fig. 1B (f)). In this experiment a NASA test pilot flew orbiter landing profiles employed in astronaut pilot training (both the HAC maneuver and final approach) with the VMS operated in full-motion mode. There were significant differences in cockpit layout of the orbiter compared to the A340. The shuttle commander uses the rotational hand controller, located between the knees, to manipulate the control surfaces during flight, whereas an A340 pilot uses a side-mounted stick. Moreover, a heads-up display (HUD) which projects critical flight information onto a small transparent screen in front of the cockpit window was installed after the sixth mission of Columbia (and in all subsequent orbiters) in response to the unique orbiter flight
During banking turns there was a consistent roll rotation of the eye and head in the same direction as the visual horizon (opposite to aircraft bank). Data from pilot 1 illustrate this phenomenon (Fig. 3A-C). During a banking turn to the right (CW) the left eye rotated CCW from the pilot’s point of view, which tended to align the retina with the horizon (Fig. 3A: panel 1). There was a corresponding roll tilt of the head in the same direction as the ocular torsion. As the pilot banked the aircraft to the left (CCW; Fig. 3A: panel 2) the head and eye rotated CW in roll (Fig. 3A-C), again toward alignment with the horizon. When performing similar banking turns in zero visibility (clouds), this spatial orientation of the head and eyes was not observed (Fig. 3E).

These results were consistent across all six subjects. Eye, head, and bank data from all 24 turns to the right

**RESULTS**

Dynamics and complex approach trajectory. The A340-300 simulator used in this study did not employ a HUD.

**Fig. 3.** A) Scene images during banking turns in the A340-300 simulator. The cross indicates pilot’s point-of-regard; orientation of the cross represents roll eye position in head coordinates (X10). B) Corresponding roll tilt of the head toward the horizon (X10). C) Aircraft bank angle, head-in-space, and eye-in-head roll position data from the pilot in A; numbered cursors indicate temporal location of the three scene images. D) Bank angle, head roll tilt, and ocular torsion (mean and 95%CI of all six subjects) expressed as a percentage of bank duration. E) Roll tilt of the head and eyes were not observed when banking in zero visibility (clouds).
and 24 turns to the left were interpolated and resampled (1000 points per turn) to compute the mean response across all pilots as a percentage of turn duration (Fig. 3D). When banking to the right (CW) there was a steady roll of the aircraft that reached a plateau approximately 25% into the turn. The eye and head rotated in the opposite (CCW) direction, reaching a relatively stable value that was maintained throughout the plateau phase. These movements were reversed as the pilots banked left (CCW).

There were no significant differences ($P > 0.1$) in aircraft, eye, or head movement magnitudes during turns to the right or left; therefore, data from all 48 turns were pooled for analysis. The peak roll rate of the aircraft, eye, and head when transitioning from a bank to the right (or left) to the opposite direction were calculated for each turn from the slope of a linear least squares fit to the position data. Peak aircraft bank angle and peak roll of the eye and head were determined from the mean of the position data during the plateau phase. Peak aircraft roll velocity ranged from $7.2$ to $17.3^\circ \cdot s^{-1}$ [10.9$^\circ \cdot s^{-1}$ (CI 2.3); mean and 95%CI of 48 turns from all pilots] with a final bank angle ranging from $34.5^\circ$ to $46.6^\circ$ [41.3$^\circ$ (CI 2.6)]. Roll eye velocity ranged from $0.6$ to $2.3^\circ \cdot s^{-1}$ [1.0$^\circ \cdot s^{-1}$ (CI 0.52)], and ocular torsion plateaued at $0.5$ to $3.7^\circ$ [2.0$^\circ$ (CI 0.66)]. Head roll velocity ranged from $0.5$ to $2.9^\circ \cdot s^{-1}$.
[1.2° · s⁻¹ (CI 0.53)] and peak head roll from 1.1 to 9.0° [3.6° (CI 1.64)]. Linear regression demonstrated that peak roll eye position for each subject was inversely correlated with peak head tilt (R = −0.89; P = 0.0005); the larger the roll of the head, the smaller the ocular torsion. The combined head and eye roll velocity toward the horizon ranged from 1.2 to 3.8° · s⁻¹ [2.2° · s⁻¹ (CI 0.55)] and the magnitude of head plus eye roll position during the plateau phase was 3.5 to 9.5° [5.5° (CI 1.1)]. The gain of the roll eye velocity response (peak eye velocity divided by peak aircraft bank velocity) ranged from 0.01 to 0.19 [0.10 (CI 0.03)]; the roll eye position gain (peak torsion divided by plateaue bank angle) was 0.01 to 0.08 [0.05 (CI 0.02)]. Head roll velocity gain ranged from 0.05 to 0.32 [0.12 (CI 0.06)], and head position gain from 0.03 to 0.23 [0.09 (CI 0.04)]. Combined head and eye roll velocity gain ranged from 0.15 to 0.32 [0.22 (CI 0.04)], and head plus eye roll position gain from 0.07 to 0.23 [0.14 (CI 0.03)].

All pilots were able to land the A340 simulator using the modified orbiter final approach (Fig. 3A), with simulated touchdown speeds ranging from 188 to 203 kn [194 kn (CI 5)]. There were small movements of the cabin in space generated by simulated turbulence (Table I). Cabin vertical linear acceleration (RMS of 60 s of data; mean of all six landings) was 0.16 m · s⁻² after subtracting the 9.8 m · s⁻² of gravity). Cabin RMS angular velocities were less than 1° · s⁻¹. Angular velocities of the head were significantly larger (P = 0.001; > 11° · s⁻¹ RMS in pitch and yaw), reflecting the active nature of head motion. RMS head angular position was less than 6°, although maximum values were considerably larger (up to 81° in one pilot) in response to transient motion of the cabin at touchdown or when fixating the overhead instrument panels (Table I; large maximum values for head pitch velocity and position).

Data from pilot 4 illustrate head-eye coordination during landing (Fig. 4A-E). During final approach there were small rotations (< 5°) of the head in pitch and yaw (Fig. 4C). The pilot made a large (~50°) transient upward head pitch movement 50 s prior to preflare to fixate on the overhead panel. Vertical saccadic eye movements (~50°) alternated gaze between the instruments [PFD and navigation display (ND)] and the approaching runway (Fig. 4B and D). There were a series of smaller horizontal saccadic eye movements (~20°) that directed gaze to the right when fixating the runway and to the left when checking the instruments (Fig. 4D). The pilot spent more time fixated on the runway after the preflare maneuver, and almost exclusively so after touchdown (Fig. 4B and D). Superimposed on these active eye movements throughout the final approach were small compensatory vertical eye rotations in response to head pitch (the vestibulo-ocular reflex; Fig. 4E). During rollout, vertical optokinetic nystagmus with downward slow phases (peak velocity 6.1° · s⁻¹) was apparent (Fig. 4E) as the pilot fixated on the centerline of the runway.

This pattern of head-eye coordination was consistent across all six subjects. A binary function was created for vertical gaze from each of the six simulated landings such that ‘1’ represented looking at the runway (outside) and ‘0’ signified that the pilot was fixating on the instrument panel (inside). Aligning all six traces at touchdown and averaging provided the probability of the pilots looking inside or outside at any particular point during the landing (Fig. 4F). During the steep approach, gaze alternated between the runway and the instruments. There was no significant difference (P = 0.82) in time spent looking inside or outside, with pilots spending an average of 52% (CI 19) of the time fixating on the runway (mean of 217 s of data prior to preflare). After the preflare maneuver, approximately 50 s prior to touchdown, subjects fixated primarily on the runway [P = 0.006; 74% (CI 16); mean of 80 s of data], with only occasional glances at the instruments [26% (CI 16)].

Data was obtained from a single subject during simulated orbiter landings in the VMS at NASA Ames using landing profiles employed in astronaut pilot training. During the HAC maneuver over the Atlantic Ocean (to align with the runway at Kennedy Space Center), there was a sustained CCW 43° bank of the orbiter (Fig. 5A). The pilot’s head tilted CW 4.5° toward the horizon (in the opposite direction to the shuttle bank angle), with a corresponding 2.1° CW roll of the eye (Fig. 5A). The magnitude and direction of orbiter bank angle, and head and eye roll tilt, were similar to that observed in the A340 (Fig. 3D). In contrast to the A340 HAC simulations, the pilot fixated the shuttle icon in the center of the HUD rather than the horizon.

During simulated final approach at Edwards Air Force Base, the suppressive effect of the HUD on pitch head and eye movements was readily apparent (compare the vertical eye movement trace from Fig. 5B with that of Fig. 4D). Head yaw (1.1° RMS, max 2.7°; calculated from 60 s of data prior to preflare) and pitch position (1.3° RMS,

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### TABLE I. MOVEMENT OF THE A340-300 SIMULATOR CABIN AND THE HEAD DURING FINAL APPROACH.

<table>
<thead>
<tr>
<th>Acceleration (m · s⁻²)</th>
<th>Angular Velocity (° · s⁻¹)</th>
<th>Angular Position (°)</th>
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<tr>
<td><strong>Z</strong></td>
<td><strong>Max</strong></td>
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<tr>
<td>Cabin</td>
<td>CI</td>
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<tr>
<td>Head</td>
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Data are mean RMS and maximum (max) values over a 60-s epoch during the steep 11° glide slope for all six pilots, plus 95% CI. Z—vertical linear acceleration (with gravitational component subtracted); Yv—yaw velocity; Py—pitch velocity; Rv—roll velocity; Y—yaw position; P—pitch position; R—roll position.
max $7.9^\circ$) were minimal, and considerably smaller than that observed in the A340 during final approach (Table I). Eye movements were also constrained as the pilot fixated on the shuttle icon throughout the approach and landing, with only occasional vertical saccades that primarily directed gaze at the approaching runway (Fig. 5B). After touchdown there were large vertical saccades between the HUD and the runway during de-rotation (where the nose gear is lowered to the runway after main gear touchdown), then horizontal saccades to the right as the pilot fixated on the runway length markers (Fig. 5B).

A simulated HUD failure revealed more complex gaze strategies. The pilot concentrated gaze on the start of the runway during simulated final approach at Edwards Air Force Base as the copilot called out altitude and airspeed. Approximately 35 s prior to touchdown the pilot made downward saccades to alternate gaze between the start of the runway and the aim point, a visual ground marker 1600 m short of the runway (Fig. 5C; phase I). After passing over the aim point the pilot continued to fixate on the start of the runway while making upward saccades to briefly fixate on the end of the runway (Fig. 5C; phase II). The changing angles subtended by these vertical saccades were likely used to estimate angle of approach and speed in the absence of the HUD. Once over the runway horizontal saccades were made

Fig. 5. Simulated orbiter landing in the VMS. A) From left to right: head tilt during the HAC maneuver ($\times 10$); image detail from the scene camera showing the HUD, with the cross indicating fixation and torsional eye position ($\times 10$); corresponding animation of the orbiter generated by the VMS. B) Eye movements were suppressed during final approach and landing with a HUD. C) Eye movements during approach and landing with a simulated HUD failure.
between the center and edge of the runway (Fig. 5C; phase III) to maintain alignment of the orbiter with the runway centerline. Head yaw (1.3° RMS, max 4.4°) and pitch (1.9° RMS, max 4.2°) during final approach were only slightly larger than that observed with a functional HUD, which may reflect an emphasis on the importance of minimizing head motion in shuttle pilot training.

DISCUSSION

During simulated banking the GIA (in this instance the gravitational vertical) is aligned with the cockpit vertical; similarly, in actual banking maneuvers the GIA roll-tilts into the turn (due to the centripetal acceleration component) and is also aligned with the cockpit vertical. In both cases the visual horizon (viewed through the cockpit window) tilts in roll in the opposite direction to the aircraft bank angle. Consistent with previous studies (1,11,12,28,30), there was a roll tilt of the head toward the horizon (and, therefore, away from the GIA) during sustained banking turns that was not anticipatory. A novel result was the corresponding rotation of the eye in the same direction as head roll, observed in both the A340 and the orbiter, which was not diminished by the HUD. Together these orienting head and eye movements tended to tilt the retina toward the horizon when looking outside the cockpit window with a gain of 0.14 of bank angle. The drive for these reflexive movements was visual, as demonstrated by the lack of head and eye roll when performing banking maneuvers in zero visibility (Fig. 3E). The roll of the head and eyes likely represents a tendency to align the retina with the Earth horizon to improve spatial orientation by establishing the retinal image of the horizon as a primary visuo-spatial cue (11).

A recent study (26) demonstrated sustained ocular torsion (~1°) toward the ‘pictorial’ vertical, when viewing statically tilted scenes, that was larger for images with strong spatial cues (landscapes, water, buildings). The authors surmised that the increased response to these spatial cues was suggestive of an otolithic basis for the eye movements, as proposed earlier by Crone (10); that is, viewing a statically tilted landscape was interpreted by the brain as a body tilt in the opposite direction. This implies that the visually driven ocular roll response may share some neural pathways with the otolithic tilt reflex. The dynamic head and eye roll response to the rotating visual scene when transitioning from one sustained bank angle to another was consistent with the optokinetic reflex, which shares many of the same neural pathways as the angular (semicircular canal mediated) vestibulo-ocular reflex (29). The gain of slow phase torsional eye velocity in response to a rotating visual scene has been reported as 0.12 (6), consistent with roll eye velocity gain of 0.10 in the current study (head roll velocity gain was 0.12). Torsional eye velocity has also been observed in the same direction as a single rotating line subtending a visual angle of 19°, although with a lower gain of 0.05 (20), demonstrating that a full-field rotating visual stimulus is not required to elicit the response.

The head-eye coordination observed during banking differed significantly to that reported during circular locomotion (16). When negotiating a 50-cm radius turn the centripetal acceleration summed with gravity to tilt the GIA 20° into the turn. There was an anticipatory head roll (7°) toward the GIA, and ocular torsion (1.5°) in the same direction. However, in this instance the orientation of the head and eyes tilted the retina away from the spatial vertical and toward alignment with the GIA. The roll of the eyes was likely driven by the OCR reflex (22), responding to the tilt of the GIA relative to the head (13°). When turning a corner the head (and body) roll tilt toward the GIA likely aids postural stability, and the ocular torsion, in concert with the large (25–30°) yaw eye movement into the turn, may act to direct gaze in the intended direction of locomotion (16). Ocular torsion during aircraft banking is not an OCR response, which would drive the eyes in the opposite direction to head tilt (i.e., back toward the GIA). Thus, during the head tilts observed throughout sustained bank, OCR was either suppressed or overwhelmed by the visually driven roll eye movement.

Pilots exhibited a stereotypical pattern of head-eye coordination when performing final approach in the A340 simulator. Active head movement was small (< 6° RMS), with gaze primarily directed by large vertical saccadic eye movements between the runway and the instrument panel. Superimposed on these active fixations were eye movements compensatory for head rotation, driven by the vestibulo-ocular reflex. After preflare, pilots concentrated mostly on the approaching runway, and optokinetic nystagmus (OKN) was observed (with downward slow phases) during rollout as the pilots fixated on the runway centerline (Fig. 4E). There is a tendency for mean eye position (beating field) to shift toward the OKN quick phase direction (23), except during OKN with downward slow phase velocity (as during forward locomotion, the visual flow of the terrain in front of the subject is downward relative to the head; i.e., an upward drift of the eye is counterproductive). This suppression of upward drift of the beating field was absent on orbit (23), which may lead to difficulty maintaining gaze during shuttle rollout. The head-eye coordination strategy observed in the A340 simulator was likely representative of the first six missions of the orbiter Columbia (STS 1-5 and 9). After STS-9 a HUD was retrofitted to Columbia and included in all subsequent orbiters (17). The HUD greatly reduced the necessity for pitch head and eye movement (i.e., alternating gaze between the runway and instruments) during final approach and landing in the VMS (Fig. 5B), with the pilot fixating almost exclusively on the shuttle icon in the center of the display.

Extrapolation of the results from the current study to spatial disorientation during actual orbiter landing is limited by a number of factors: our pilot subjects were not adapted to microgravity; the flight simulators did not generate hypergravity (rapid vertical translation of the VMS during simulated preflare does generate 1.1 g, less than the 1.4 g during actual landings); and the scar-
city of data from high-fidelity (VMS) orbiter simulations. With these limitations in mind, we speculate below on how our results may relate to pilot landing performance after prolonged microgravity exposure. Head movement during orbiter reentry and landing generates illusory percepts of motion (14) that may predispose pilots to spatial disorientation. The basis for these perceptual illusions is unknown, but could reflect postflight changes in both the idiotropic vector (8) (exaggerated sensations of head tilt) and central integration of angular (semicircular canal) and linear (otolith) afferent input (21) during head motion (a possible mechanism underlying illusions of path, at least for pitch and roll head tilts relative to the gravitational vertical). Data from the NASA test pilot in the VMS suggested that implementation of the HUD minimized active head and eye movements required during final approach, possibly reducing the likelihood of self-motion triggered spatial disorientation. However, the adverse orbiter landing events cited in the Introduction occurred both prior to (‘flight B’ and after (‘flight A’) HUD installation. Thus, in addition to illusory percepts generated by head motion, shuttle pilots may be susceptible to spatial disorientation from external influences, in particular the hypergravity stages of manual orbiter control (the 1.2-g HAC maneuver and 1.4-g preflare). The HAC maneuver requires a sustained coordinated roll-tilt of the head and eyes toward the horizon, which may be degraded by exaggerated sensations of head roll due to in-flight adaptation of the idiotropic vector (8) and the g excess effect (13). Similarly, active head movement at preflare can generate significant disorientation, as evidenced by ‘flight A’ discussed earlier.

The results of this study confirm previous reports of the head roll (OKCR) response to sustained bank observed in military pilots, and extend these findings to describe a corresponding roll of the eyes toward the horizon. The orbiter HUD virtually eliminated the requirement to look inside during final approach, likely improving the safety of orbiter landings by minimizing active head motion. A greater awareness of the impact of adaptation to microgravity on head-eye coordination and motion perception during hypergravity phases of orbiter reentry and landing may be required; this is relevant to manned docking and landing maneuvers of future exploration class missions.

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