Onset of Positional Vertigo During Exposure to Combined G Loading and Chest-to-Spine Vibration

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Background: Aerospace environments commonly expose pilots to vibration and sustained acceleration, alone and in combination. ***Case Reports:*** Of 16 experimental research participants, 3 reported symptoms of vertigo and signs of torsional nystagmus during or shortly following exposure to sustained chest-to-spine (+3.8 G_x) acceleration (G loading) and chest-to-spine (0.5 g_x) vibration in the 8-16 Hz band. Two of the participants reported intermittent vertigo for up to 2 wk, were diagnosed with benign paroxysmal positional vertigo (BPPV), and were treated successfully with the Epley Maneuver. On a follow-up survey, a third participant reported transient BPPV-like vertigo, which resolved spontaneously. The follow-up survey also prompted participants to self-report other effects following research protocol exposure to vibration and G loading, revealing details about other minor and transient, but more common, effects that resolved within 3 h. ***Discussion:*** Our studies indicated a significantly elevated incidence of BPPV following exposure to vibration plus G loading compared to vibration alone that was positively correlated with participant age. One mechanism for the rolling sensation in BPPV involves broken or dislodged otoconia floating within one of the posterior semicircular canals, making the canal gravity-sensitive. Our observations highlight a heretofore unforeseen risk of otolith damage sustained during launch, undetectable in space, potentially contributing to vertigo and perceived tumbling upon re-entry from microgravity.

Keywords: BPPV, tumbling, wobblies.

AEROSPACE ENVIRONMENTS commonly expose pilots to vibration and sustained acceleration, alone and in combination. In addition to the broadband aero-acoustic vibration present in all aerospace environments, propulsion systems may introduce narrowly tuned vibration. For example, the Titan II used during the Gemini program introduced an 11-Hz pogo vibration and NASA's Ares I vehicle design was expected to introduce a 12-Hz thrust oscillation into the Orion cockpit. We ran a series of human performance experiments that exposed participants to moderate chest-to-spine (0.5 g_x) vibration at 8, 12, and 16 Hz, either lying supine in normal Earth gravity (+1 G_x) or during sustained chest-to-spine acceleration (+3.8 G_x). Our vibration conditions were designed to bracket the expected frequency range of vibration driven by rocket propulsion systems and the elevated G level represents the G load at the time of highest vibration during launch.

Of 16 (12 men, 4 women, age range: 21-57 yr) experimental research participants, 3 (all men, age range: 50-52 yr) reported initial symptoms of vertigo during or shortly following exposure to chest-to-spine (0.5 g_x at 8, 12, and 16 Hz) vibration and sustained chest-to-spine (+3.8 G_x) acceleration on the NASA Ames 20-G centrifuge. The experimental protocols were approved by the Human Research Institutional Review Board at the NASA Ames Research Center, with each subject providing written informed consent. The informed consent document stated that among foreseeable inconvenience, discomfort, and risks, participants may experience "signs and symptoms of motion sickness or vestibular disturbances during and following centrifugation such as dizziness, blurred or partial loss of vision, sweating, excessive salivation, stomach awareness, nausea and a remote chance of vomiting and unconsciousness," "pain, discomfort, or fatigue," "light-headedness" during centrifugation, and "arm and shoulder muscle soreness afterwards."

CASE REPORTS

The first case was exposed to the vibration stimulus with and without sustained acceleration during a manual pointing experiment over a period of 5 wk. The participant was exposed to seven 160-s blocks of 0.5-g_x vibration (~40 s at each vibration condition: 8, 12, 16, and no vibration) superimposed on a 1-G_x bias (lying on his back in normal Earth gravity) in the laboratory on 3 separate days, followed by 10 such blocks of vibration with a 3.8-G_x bias (in the Ames 20-G centrifuge) on 4 separate days. On each experiment day, the participant performed three blocks of the pointing task, which involved negligible cardiovascular effort at 1 G_x but significant effort at 3.8 G_x. This participant experienced a brief episode of vertigo shortly after completing the manual-pointing task on the final day of exposure to vibration at 3.8 G_x, having reported no previous episodes of vertigo. The participant's intermittent vertigo persisted for 2 wk and was treated successfully with the Epley Maneuver.

The second case was exposed to the vibration stimulus during three separate experiments (two testing

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manual pointing performance and one smooth pursuit of a target spot moving radially in the frontoparallel plane) on 9 nonconsecutive days over a period of 6 mo. In total, the participant was exposed to 16 160-s blocks of vibration at 3.8 G_x (over 5 separate days) and 13 blocks at 1 G_x (over 4 separate days). The participant first experienced a sudden-onset roll vertigo during the manual-pointing task on the final day of vibration exposure at 3.8 G_x. The vertigo reoccurred intermittently for 10 d and was triggered by lying down or looking up or down, and was treated successfully with the Epley Maneuver. This participant reported a subtle mild residual sensation of slow world motion when lying down on his side in the dark that persisted intermittently for approximately 10 mo and resolved spontaneously.

The third case was exposed to the vibration stimulus during two separate experiments (one testing manual pointing, one smooth pursuit tracking) on 7 nonconsecutive days over a period of 3 mo. In total, the participant was exposed to 13 160-s blocks of vibration at 3.8 G_x (over 4 nonconsecutive days) and 13 blocks at 1 G_x (over 4 nonconsecutive days). Although he did not report it prior to the survey (see below), this participant experienced vertigo following completion of the tracking task, noting that: the vertigo occurred when changing positions while lying down, persisted intermittently for 1-2 mo, and resolved spontaneously without medical intervention.

To assess whether the risk of benign paroxysmal positional vertigo (BPPV) occurrence increased when vibration was combined with G loading, we performed a retrospective survey to identify any unreported instances of vertigo or illusory world motion. The results of the survey revealed a third participant who experienced transient BPPV-like symptoms that had not heretofore been reported, even though all participants were repeatedly encouraged to report any such symptoms during or after their involvement in the experiment. Thus, in total, 3 out of 16 participants experienced BPPV-like vertigo following exposure to vibration plus 3.8 G_x sustained acceleration (mean probability of occurrence = 0.1875, 95% binomial confidence range: 0.09–0.42), which is significantly higher than the conservative (1%) upper bound for the annual incidence of naturally occurring BPPV based on reported prevalence (14). There were no reports from any participants of an illusion of world motion either during or immediately following exposure to vibration at 1-G_x bias (mean probability of occurrence = 0.0, 95% binomial confidence range: 0–0.17). This negative result combined with the significant positive probability suggests that combining sustained elevated G loading with vibration is a risk factor for BPPV.

Through participants' responses to a short post-study questionnaire, the survey also enabled us to document systematically the incidence and details of any other minor, transient effects of our vibration and sustained acceleration protocols. Participants were encouraged to report any symptoms to the investigators or NASA medical staff at the time of the experimental runs, but some chose not to. These self-reported effects were sufficiently benign that some were not mentioned until prompted by specific questions in our follow-up survey. For vibration alone, of the 16 participants, we found fatigue was reported by 1 participant, shoulder soreness by 1, lightheadedness/confusion by 1, muscle pain/cramping by 1, headache by 2, and illusory self-motion by 1, all of which resolved spontaneously within 3 h following the vibration-only run. Following exposure to vibration plus sustained acceleration (centrifugation), dizziness was reported by 5 of the 16 participants, headache by 2, lightheadedness/confusion by 2, fatigue by 4, arm muscle soreness by 3 following the manual-pointing task, balance problems by 4, minor back pain by 1, illusory self-motion by 1, and illusory world motion by 3. For the 13 participants without BPPV, any reported adverse effects (i.e., balance problems, dizziness, headache, and confusion) resolved spontaneously within 3 h of having finished the centrifuge run; arm/shoulder fatigue and soreness could persist for up to 4 d. For the three participants with BPPV, intermittent balance problems, dizziness, illusion of self motion, and illusion of world motion typically persisted for a few weeks. In one of the three cases, however, mild episodic illusory world motion persisted for months.

DISCUSSION

Previous reports have identified vibration as a possible etiological factor for BPPV. One report (3) documented a case of BPPV resulting from exposure to commercial vibration exercise equipment (reported frequencies in the 25-50 Hz range); the occupational literature reports illusions of movement, or balance issues arising from use of high-vibration equipment (8), riding a bike over rough terrain (9), or high-impact aerobics (17). Indeed, torn otolithic membrane and abnormal canal structure in macaques were observed after an 8-h exposure to 10-Hz vibration under intense (1-2 g) vibration conditions (12).

While normal Earth gravity (1.0 G) is sufficient to provoke symptoms of vertigo (5) or to reposition otoconia (7), all three of our BPPV cases were reported either during or immediately following exposure to vibration on the centrifuge, implicating G loading as a factor that exacerbates the risk of developing vibration-induced BPPV. In aerobatic pilots, negative (tail-to-head) G_z loading has been associated with persistent vertigo in 12.7% of pilots (18) and with BPPV in at least one diagnosed case (−7 G_z, 41-yr-old male pilot) (11), indicating that actual aerospace environments with elevated G loading and vibration do present an elevated risk for BPPV.

Interestingly, we observed that the oscillatory translational and rotational head accelerations resulting from our vibration stimuli were generally smaller (or equal) in the 3.8-G_x condition on the centrifuge than for the 1.0-G_x condition in the laboratory (**Table I**). This reduction in oscillatory head motion during centrifugation discounts the idea that a simple increase in displacement amplitude gives rise to a larger input to the vestibular system. The increased BPPV incidence during G loading despite the reduction in head motion may be attributable

TABLE I. TRANSLATIONAL AND ROTATIONAL MOVEMENTS OF THE HEAD DURING VIBRATION.

	X-Axis Vibration		Lateral	Vertical	Depth	Pitch	Roll	Yaw
			Left-Right	Cephalo-Caudal	Anterior-Posterior			
G_x Load	Frequency (Hz)	Participant	mm (g)	mm (g)	mm (g)	degrees ($° \cdot s^{-1}$)	degrees ($° \cdot s^{-1}$)	degrees ($° \cdot s^{-1}$)
3.8	8	1	0.2 (0.1)	0.1 (0.0)	2.5 (0.6)	0.4 (20)	0.4 (21)	0.5 (25)
		2	0.6 (0.2)	0.1 (0.0)	1.7 (0.4)	0.1 (6)	0.3 (2)	0.3 (16)
		3	0.4 (0.1)	0.4 (0.1)	1.6 (0.4)	0.1 (3)	0.1 (3)	0.3 (13)
	12	1	0.1 (0.0)	0.4 (0.2)	1.3 (0.7)	0.3 (25)	0.2 (16)	1.1 (81)
		2	0.2 (0.1)	0.4 (0.3)	0.8 (0.5)	0.3 (25)	0.1 (5)	0.1 (9)
		3	0.1 (0.1)	0.8 (0.5)	1.8 (1.1)	0.1 (10)	0.2 (12)	0.7 (53)
	16	1	0.0 (0.0)	0.2 (0.2)	0.6 (0.6)	0.2 (24)	0.2 (19)	0.4 (43)
		2	0.1 (0.1)	0.3 (0.3)	0.7 (0.7)	0.3 (34)	0.1 (8)	0.2 (18)
		3	0.1 (0.1)	0.4 (0.4)	0.7 (0.7)	0.1 (9)	0.1 (10)	0.4 (42)
1.0	8	1	0.6 (0.2)	1.1 (0.3)	2.5 (0.6)	1.0 (49)	0.2 (7)	0.6 (31)
		2	0.5 (0.1)	0.6 (0.2)	2.3 (0.6)	0.3 (14)	0.2 (7)	0.3 (14)
		3	0.3 (0.1)	2.2 (0.6)	3.0 (0.8)	1.0 (47)	0.2 (9)	0.4 (22)
	12	1	0.2 (0.1)	1.2 (0.7)	1.7 (1.0)	0.5 (39)	0.2 (12)	0.2 (15)
		2	0.2 (0.1)	1.4 (0.8)	1.9 (1.1)	0.3 (23)	0.1 (6)	0.2 (13)
		3	0.2 (0.1)	1.2 (0.7)	1.5 (0.9)	0.4 (28)	0.1 (9)	0.0 (2)
	16	1	0.2 (0.2)	0.7 (0.7)	0.7 (0.7)	0.4 (38)	0.1 (11)	0.1 (13)
		2	0.1 (0.1)	0.8 (0.8)	0.8 (0.8)	0.1 (12)	0.1 (5)	0.1 (7)
		3	0.1 (0.1)	0.9 (1.0)	0.8 (0.8)	0.2 (19)	0.2 (16)	0.1 (13)

We used a video-based tracking system (10) to measure the translational and rotational displacements of the head during this task for the three participants with BPPV. For translational movements, displacement amplitudes (0-to-peak, in mm) are given along with translational accelerations (in g). For rotational movements, displacement amplitudes (0-to-peak, in degrees) are given along with rotational velocities (in $° \cdot s^{-1}$). For the 3.8-G_x condition, displacements are given for the block of ~60 trials immediately preceding the onset of symptoms and a matched block of trials in the fixed-base condition. The SEM of these measurements ranged from 1 to 15% of the mean value. For these participants, translational and rotational displacements in the 1.0-G_x condition are generally larger than or equal to those in the 3.8-G_x condition.

to one of several mechanisms, which may have contributed to amplification of the oscillatory response of the otolith organs during vibration at elevated G levels. First, following Vykukal (15) and Vogt et al. (13), elevated G loading may increase the resonant frequency of otolith organs, thereby moving the resonance into the range of one of our vibration frequencies. Second, again following Vykukal (15) and Vogt et al. (13), elevated G loading may reduce the structural damping of the otolith organs, which in turn would elevate their oscillatory response to a given vibration input. Finally, increased stiffness of the otolith organs under G loading may increase the brittleness of the crystal layer, leading to broken or dislodged otoconia.

To compare the number of participants exposed to our combined vibration and G-loading conditions with exposures in the previous literature, we documented the complete set of controlled experiments, to the best of our knowledge, that have exposed participants to combined vibration and G loading (**Table II**). Conditions similar to our 12-Hz vibration condition (0.5 g_x at a 12-Hz vibration at a constant 3.8 G_x) have been used extensively for previous spacecraft development programs. The Gemini program (4,16) employed 11-Hz vibration stimuli (amplitude of 0 to 1.6 g_x plus substantial harmonic content) superimposed on a bias G load of 3.85 G_x. Biodynamic response experiments at NASA (15) used a broader vibration frequency range (2.5–20 Hz) and similar (1–4 G_x) G-bias conditions, including four participants tested at both 8 and 16 Hz. Recent studies at NASA Ames in support of the Constellation program exposed participants to 12-Hz vibration at amplitudes up to 0.7 g_x under G-bias conditions identical to the current study (1,2). None of these previous vibration plus G loading studies carried out at NASA Ames [Gemini crew performance (16), $N = 7$; pilot control performance (6,16), $N = 5$; dial reading (4,16), $N = 6$; human body dymanics (15,16), $N = 4$; reading

TABLE II. STUDIES WITH EXPOSURE TO COMBINED G_X BIAS LOADING AND *X*-AXIS VIBRATION.

Experiment (Reference)	*N*	Vibration Frequency (Hz)	Vibration Amplitude (g_x)	Sustained G_x Load
Gemini crew performance (16)	7	11	0.14–1.65	3.5
Pilot control performance (6,16)	5	11	0–3.0	1, 2, 3.5
Dial reading (4.16)	6	11	0.8–3.0	3.85
Human body dynamics (15,16)	4	2.5–20	0.4	1, 2.5, 4
Reading and visual performance (1.2)	31	12	0.15–0.7	1, 3.8
Current study	16	8, 12, 16	0.5	1, 3.8

Vibration in the 11-12 Hz frequency band has been tested repeatedly, with over 50 participants exposed over the past five decades in support of the Gemini and Constellation programs, without reported post-run positional vertigo. The current study introduced two new vibration frequencies, 8 and 16 Hz, which were previously tested on four participants at 0.4 g_x (15).

and visual performance (1,2), $N = 31$; total, $N = 53$] noted instances of sustained vertigo or other vestibular disturbances, although a systematic retrospective survey of the 2009 studies would be needed to confirm this. It is noteworthy that two of our three participants diagnosed with BPPV also took part in the 2009 NASA Ames studies (2) that exposed them to 0.7-g_x vibration superimposed on a 3.8-G_x bias without reporting sustained vertigo or other vestibular disturbances.

Although our three cases do not provide sufficient power to identify the exact factor(s) within our stimulus set (e.g., vibration frequency, cumulative exposure to vibration, manual pointing activity, exposure to sustained 3.8-G_x bias) or the interactions responsible for the increased risk of BPPV, we must note that participant age is a critical factor. For our 16 participants, a correlation analysis of BPPV incidence and age reveals a significant effect (Spearman's rank correlation, $r_s = 0.588$, $N = 16$, $P < 0.05$) consistent with previous reports of age being a risk factor for BPPV, with the incidence/prevalence increasing sharply above age 40 (14). These cases highlight the greater risk of older crewmembers developing BPPV resulting from exposure to vibration plus G loading, a risk factor that may become even more relevant as commercial space companies consider older space tourists. Finally, we must raise the potential risk that otolith damage sustained during launch, which would increase canal sensitivity to gravity loading, might remain undetected until the crew re-enters the nonzero gravity of Earth, Moon, or Mars. The resulting sudden attack of vertigo, nominally benign, could, however, have far greater consequences for a pilot and crew.

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