Relative Severity of Human Performance Decrements Recorded in Rapid vs. Gradual Decompression

Jeremy Beer; Andrew J. Mojica; Kara J. Blacker; Todd S. Dart; Bria G. Morse; Paul M. Sherman

INTRODUCTION: Cabin decompression presents a threat in high-altitude-capable aircraft. A chamber study was performed to compare effects of rapid (RD) vs. gradual decompression and gauge impairment at altitude with and without hypoxia, as well as to assess recovery.

METHODS: There were 12 participants who completed RD (1 s) and Gradual (3 min 12 s) ascents from 2743–7620 m (9000–25000 ft) altitude pressures while breathing air or 100% O_2. Physiological indices included oxygen saturation (S_PO_2), heart rate (HR), respiration, end tidal O_2 and CO_2 partial pressures, and electroencephalography (EEG). Cognition was evaluated using SYNWIN, which combines memory, arithmetic, visual, and auditory tasks. The study incorporated ascent rate (RD, gradual), breathing gas (air, 100% O_2) and epoch (ground-level, pre-breathe, ascent-altitude, recovery) as factors.

RESULTS: Physiological effects in hypoxic "air" ascents included decreased S_PO_2 and end tidal O_2 and CO_2 partial pressures (hypocapnia), with elevated HR and minute ventilation ($\dot{V}_E$); S_PO_2 and HR effects were greater after RD (−7.3% lower and +10.0 bpm higher, respectively). HR and $\dot{V}_E$ decreased during recovery. SYNWIN performance declined during ascent in air, with key metrics, including composite score, falling further (−75% vs. −50%) after RD. Broad cognitive impairment was not recorded on 100% O_2, nor in recovery. EEG signals showed increased slow-wave activity during hypoxia.

DISCUSSION: In hypoxic exposures, RD impaired performance more than gradual ascent. Hypobaria did not comprehensively impair performance without hypoxia. Lingering impairment was not observed during recovery, but HR and $\dot{V}_E$ metrics suggested compensatory slowing following altitude stress. Participants' cognitive strategy shifted as hypoxia progressed, with efficiency giving way to "satisficing," redistributing effort to easier tasks.

KEYWORDS: hypoxia, rapid decompression, hypocapnia, hyperventilation, cognitive strategy.

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In pressurized aircraft, loss of cabin pressure at high altitude presents risks; in a small cockpit, the potential consequences of rapid decompression (RD) are grave, culminating in aircrew members' loss of effectiveness, consciousness, and even life.[17] Although decompressions are rare,[9] the threat is amplified when the O_2 pressure in the inspired gas (P_IO_2) is lower, when decompression reaches a higher altitude, and when the rate of decompression is higher.[22]

Understanding the effects of low P_IO_2 on hypoxia severity at terminal altitude appears straightforward, since this determines the partial pressure of oxygen in the alveoli after decompression.[11,13,15] By contrast, the effect of decompression rate on aircrew performance is less clear. One reason for this is that the time of useful consciousness (TUC)—a blanket term intended to represent the time from O_2 interruption until loss of ability to take corrective action, which has remained a hypoxia impairment metric in aviation since World War II—remains vaguely and variously defined[31] and subject to individual differences.[16] Textbook citations state that hypoxia effects are greater in rapid vs. gradual decompression,[15,17,22] but these assertions are largely based on earlier studies[6,13] which, albeit meticulously described, employed nonuniform cognitive metrics and small samples (five and three subjects, respectively).

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This indicates a need to better assess cognitive deterioration during rapid ascents to high altitude and compare this to the impairment recorded in more gradual ascents, using a larger sample with greater statistical power. In addition, it is desirable to determine whether effects from high-altitude ascent are attributable solely to hypoxia or, alternatively, could result from low ambient pressure without hypoxia. The possible independent effect of barometric pressure is suggested by findings indicating that hypobaric and normobaric hypoxia effects are not identical[31]; in this study, we examine only hypobaric effects as experienced at altitude or in a chamber. There is also a need to continue investigating the potential for lingering impairment during recovery from hypoxic exposure. This has been referred to as "hypoxia hangover," has been reported at varying severity levels,[10,27,36] and has been linked to the occurrence of hypocapnia.[4,35]

In this study, neurocognitive and physiological instruments were employed throughout and after hypobaric chamber ascents to test whether RDs induce greater disruption than slower decompressions. The study addressed the three questions posed above: 1) would RD impair human performance more than gradual ascent; 2) would hypobaria affect performance in the absence of hypoxia; and 3) would hypoxia impairment linger into recovery?

METHODS

Effects from RD-vs.-gradual ascent and from hypoxic-vs.-nonhypoxic decompression were compared in a repeated-measures, within-subject design by exposing subjects to all possible combinations of these two factors in four experimental hypobaric exposures (hereafter referred to as flights) leading to a terminal altitude pressure equivalent to 7620 m (25000 ft). Physiology markers were recorded throughout exposure, including: oxygen saturation (S_PO_2); heart rate (HR); end-tidal partial pressures for O_2 ($P_{et}O_2$) and CO_2 ($P_{et}CO_2$), which are respiratory indicators of hypoxia and hypocapnia, respectively; respiration rate (*f*); estimated tidal volume (V_T); and minute ventilation ($\dot{V}_E$). The cognitive test instrument was a synthetic workstation called SYNWIN, on which participants performed throughout exposure to enable monitoring of the time course of impairment and recovery. SYNWIN is sensitive for detecting cognitive manifestations of hypoxia[2] and was employed here because it assesses performance in four distinct cognitive tasks and overall executive function, at a sampling resolution finer than 1 min. The study also included electroencephalogram (EEG) recording of the spectral distribution of cortical electrical activity, which is sensitive to reduced oxygen supply via spectral power changes[20,24] and event-related potentials that track sensory processing.[7,30] EEG was measured to detect changes in brain function that might be linked to cognitive deficits during hypoxia. All flights continued physiological and neurocognitive monitoring through a postexposure recovery epoch to identify lingering impairment or other effects.

Subjects

The study protocol was approved by Air Force Research Laboratory 711th Human Performance Wing Institutional Review Board. Each subject provided informed consent before participating. There were 12 nonsmoking U.S. Air Force volunteers, ages 27–40 (mean = 32.3, SD = 3.7, 11 men, 1 woman) enrolled from Brooks High-Altitude Chamber Human Subject Panel, which requires physical qualification and hypobaric training for research participation. Two subjects wore vision correction; two were slightly myopic but participated without correction. Subjects were instructed to forego participation if they were insufficiently rested or had consumed alcohol or excessive caffeine in the 24 h before testing. Subjects completed seven sessions. The first three sessions presented training on SYNWIN, which requires practice to achieve proficiency (defined as reaching a performance plateau to minimize the noise contribution of learning across test blocks[5]). In the last four sessions, subjects completed solo test flights accompanied only by a safety observer.

Equipment and Procedures

Flights were conducted in Hypobaric Chamber A5 at Brooks Aerospace Environment Protection Laboratory, San Antonio, TX. Flights were scheduled with at least 44 h of recovery time separating them. The study employed a within-subjects, repeated-measures design with three independent factors. The first was ascent rate, which followed one of two profiles: RD or gradual ascent (described below). The second factor was a two-level breathing gas manipulation to test whether altitude effects were entirely attributable to hypoxia: subjects completed ascents in both 21% O_2 ("air") and "100% O_2" conditions. Crossing the ascent rate and breathing gas factors yielded the four flight conditions: RD Air, Gradual Air, RD 100%, Gradual 100%.

The third factor was time within each flight. This encompassed four epochs including a starting period at ground-level pressure (GLP; Epoch #1); then a "pre-breathe" Epoch #2 conducted at 2743 m (9000 ft) using 100% O_2 to reduce risk of decompression sickness; then ascent (RD or gradual) to a terminal altitude of 7620 m (25000 ft), selected to induce rapid, dramatic effects[31] (Epochs #3A and #3); and finally a recovery Epoch #4 following return to GLP (**Fig. 1**).

The altitude epoch was bounded in two ways. To represent physiological and cognitive indices over time, including the period of decompression, an "ascent-plus-altitude" Epoch #3A was defined, which began with departure from 2743 m altitude and ended when one of the exposure termination criteria occurred. To enable comparison of EEG signal characteristics among steady-state ambient conditions, altitude Epoch #3 was defined starting with arrival at 7620 m and ending with test termination. Most metrics did not vary significantly in "100% O_2" conditions, so data were analyzed independently between breathing gas conditions with an emphasis on hypoxia-inducing "air" flights. Conditions' presentation order was counterbalanced to the extent possible; counterbalancing was incomplete because some participants were substituted due to

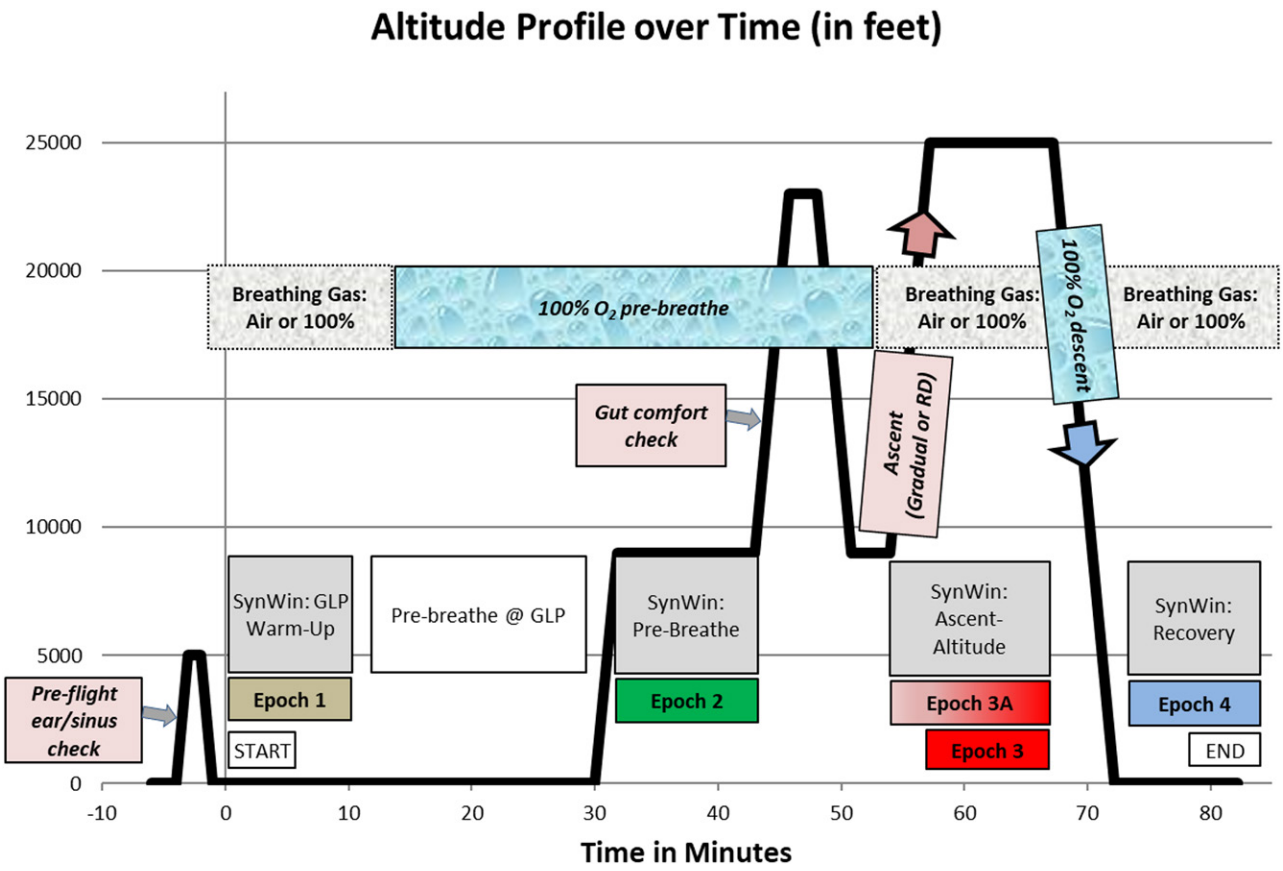

Fig. 1. Time course of epochs and events comprising a test flight, including epochs of SYNWIN performance: #1 (baseline glp), #2 (pre-breathe), #3A (ascent-altitude), and #4 (recovery). Note breathing gas manipulation (air vs. 100% O_2) and administration of 100% O_2 during pre-breathe and descent. Note that the ascent event indicates gradual or RD; this figure depicts gradual ascent requiring 3 min 12 s. Ascent time is represented in the different lengths of Epochs #3A (used in analyses of physiological and cognitive metrics) vs. #3 (used in EEG analysis).

deployment, reassignment, or medical delays. Subjects were blind to the conditions they would experience; in all flights, they were instructed to prepare for RD.

Before each flight, an EEG cap was placed on the subject, followed by an MBU-20/P aviator's mask secured by a harness, a breathing hose, and a CRU-60 connector. The mask was connected to a CRU-73 regulator during Epochs GLP (#1), altitude (#3/3A), and recovery (#4); in the two "air" flights, this regulator was connected to a supply of filtered air (21% O_2), and in the two "100% O_2" flights, a supply of aviator's breathing oxygen. During pre-breathe (Epoch #2) and descent from altitude in all flights, the mask connection was switched to an A-14 regulator delivering 100% O_2. These changes in breathing source were performed by a safety observer in the chamber who switched the breathing hose between the two regulators. Both regulators were set to demand-only mode.

Flights were governed by a timed script in which all chamber events and transitions were initiated using synchronized timing devices and their occurrence recorded in an event log. Each flight began with a 1-min period to register EEG signal characteristics of motor artifacts; subjects looked up–down and left–right repeatedly and then clenched their jaws. This was followed by 2 min of eyes-open resting state EEG data collection; subjects were asked to remain still, gaze forward, and avoid distractions. The flight epochs were then initiated: first, the subject performed SYNWIN for 10 min in GLP conditions during Epoch #1. The subject was then instructed to pause SYNWIN and was switched to the A-14 regulator to "pre-breathe" 100% O_2 for 30 min to reduce decompression sickness hazard. This switching protocol was adopted to maintain uniformity across conditions; in "100% O_2" flights, it resulted in breathing sources being switched between regulators delivering identical 100% O_2 concentrations. Then, 20 min after this hose switch, ascent to the first altitude plateau was initiated; chamber pressure was reduced at an ascent rate equivalent to 1524 m (5000 ft) per min. Upon arrival at 2743 m (9000 ft) equivalent altitude, the subject resumed SYNWIN; the ensuing 10 min of data collection comprised pre-breathe Epoch #2. The subject then paused SYNWIN, and a gradual "gut gas check" ascent to 7010 m (23000 ft) and back to 2743 m was initiated to ensure the subject was not retaining excessive abdominal gas. Subject breathing gas supply was then switched back to the CRU-73 to deliver the flight's assigned breathing mixture. The subject was instructed to resume SYNWIN and prepare for decompression. Investigators initiated a 3-s countdown, and a 5-psi decompression was initiated from 2743 m to 7620 m. In "gradual" flights, ascent proceeded at 1524 m · min^{-1}, requiring 192 s (3 min 12 s). In "RD" flights, ascent was completed in 1 s. Following arrival at

7620 m, the subject continued SYNWIN until termination of altitude exposure.

Termination was triggered, and the time recorded, when any of the following occurred: S_PO_2 (at finger) remained below 60% for 10 s; $P_{et}O_2$ remained below 30 mmHg for 10 s; discomfort or unresponsiveness; or 10 min of exposure. In a gradual flight in which the first termination criterion occurred 3 min after arrival at 7620 m, Epoch #3A would be recorded as 6 min 12 s (372 s) in duration, whereas Epoch #3 would be 3 min (180 s) long. If this flight were an RD flight where termination occurred 3 min after arrival at 7620 m, Epoch #3A and #3 durations would be recorded as 3 min 1 s and 3 min, respectively.

Upon termination, descent was initiated at 1524 m · min^{-1}, unless the subject experienced sinus pain, in which case recompression was slowed. Breathing supply was changed to the A-14 regulator to deliver a safety supply of 100% O_2 throughout descent, and the subject was asked to pause SYNWIN. Upon return to GLP, breathing supply was returned to the CRU-73 regulator test gas and the subject resumed SYNWIN throughout a 10-min recovery epoch.

All timed recording devices were synchronized before each flight. Mask flow was recorded using a Fleisch pneumotachograph (flow meter) interposed between the CRU-73 regulator and mask. Mask gases and pressure were sampled using tap lines leading from the mask to an Extrel MAX300-LG mass spectrophotometer and Validyne pressure transducer, which were calibrated on each test day. Respiration and gas data channels (mask inflow, pressure, % O_2, % CO_2) were recorded at 100 Hz via LabVIEW script. S_PO_2 and HR were recorded at 1 Hz using a MasimoSET® Rainbow oximeter on the index finger of the nondominant hand to avoid impeding SYNWIN's mouse interface.

The SYNWIN synthetic workstation combines four simultaneous cognitive tasks which the subject performs using mouse clicks (**Fig. 2**).[5,12,38] On the upper left quadrant of the workstation screen is a short-term memory task. The subject studies a list of six letters for 5 s, the list is removed, and the subject identifies subsequent probe letters as members of the list (requiring "Yes" selection) or nonmembers (requiring "No" selection). On the upper right is a mathematics task where the subject adds two numbers, scrolling to select each digit. On the lower left is a visual monitoring task where the subject monitors a gauge whose pointer sinks from 100 to 0. Subjects gain points by resetting the pointer; the closer it approaches zero, the more points accrue, but if it reaches zero, the subject loses points until the gauge is reset. At the lower right is an auditory monitoring task where the subject attends for one of two tones presented randomly: the subject avoids responding to low tones and clicks "Alert" within 3 s if a high tone plays. In all tasks, auditory feedback indicates incorrect responses.

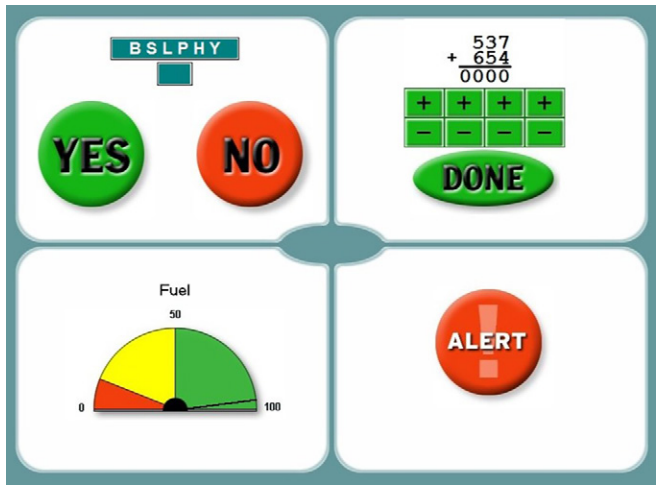

Fig. 2. The SYNWIN synthetic workstation. Tasks include memory (upper left); mathematics (upper right); visual monitoring (lower left); and auditory monitoring (lower right).

Statistical Analyses

Physiological, cognitive, and EEG datasets were screened for quality control before analyses to identify cases of dropout or compromised SYNWIN data, EEG signal artifacts, and outliers. Mean S_PO_2 and HR values were calculated across each epoch. Respiration metrics were calculated in postprocessing using temporal analysis of flow and spectrophotometric data. Time boundaries for each breath were assigned between maxima of mask inflow, at which points the CO_2 concentration peaked. Each breath was assigned a time stamp at maximum inhalation. Respiration rate (*f*) was calculated in breaths per minute using time between successive breaths. Tidal volume (V_T) was recorded in liters per breath by integrating mask flow across each breath. Minute ventilation ($\dot{V}_E$) in liters per minute comprised the product of *f* and V_T. A peak-finding algorithm was applied to the spectrophotometry data to identify minimum O_2 and maximum CO_2 concentrations in each breath. These were entered in a conversion equation accounting for water vapor pressure at 37°C to calculate $P_{et}O_2$ and $P_{et}CO_2$. Mean *f*, V_T, $\dot{V}_E$, $P_{et}O_2$, and $P_{et}CO_2$ were calculated across breaths within each epoch.

Distributions for S_PO_2, HR, *f*, V_T, $\dot{V}_E$, $P_{et}O_2$, and $P_{et}CO_2$ were viewed via boxplots, means, and standard deviations in exploratory data analysis. "Air" (21% O_2) and "100% O_2" conditions were considered separately, with an emphasis on the former, to recognize that expected physiological effects apart from HR were negligible in "100% O_2" conditions. For physiological analyses, GLP Epoch #1 was considered the baseline condition and Epoch #3A was considered to represent subjects' physiological state throughout ascent and altitude exposure. It is noted that no respiration data were available for the pre-breathe Epoch #2 since subjects were breathing from a separate regulator with no flow meter. Analyses comprised two-way repeated-measures 2 × 3 ANOVAs of data from "air" flights, using ascent rate (RD vs. gradual) and Epoch (baseline GLP vs. ascent/altitude vs. recovery) as independent factors. Post hoc comparisons were performed (two-tailed, $\alpha = 0.05$) to assess differences between baseline (Epoch #1) vs. ascent/altitude (Epoch #3A) means and thereby gauge the extent of altitude effects; between baseline vs. recovery (Epoch #4) means to identify physiological effects lingering after exposure; and between means

recorded during Epoch #3A, in RD vs. gradual conditions, to determine whether altitude-related physiological changes differed at the two ascent rates. Note that when post hoc tests were performed, least significant difference (LSD) contrasts were employed for maximal sensitivity; these contrasts, which are equivalent to *t*-tests, did not employ correction for multiple comparisons and thus slightly increased the chance of Type I Error.

In SYNWIN, a Composite Score represents performance across all tasks, including points earned minus error penalties (incorrect/missed memory identifications, incorrect mathematics sums, visual monitoring lapses, auditory false alarms/misses). Additional metrics gauge individual task performance: memory, mathematics, and auditory tasks generate scores representing throughput and accuracy, and response times (RTs) for correct responses. Visual monitoring scores indicate how effectively subjects can time responses, including avoiding lapses. Dwell time is recorded for all tasks to represent the amount of time the subject spends on each.

SYNWIN data were recorded at 20-s intervals across all epochs as described: GLP (Epoch #1), pre-breathe (#2), ascent/altitude (Epoch #3A includes ascent to 7620 m and the time spent there until termination) and recovery (#4). Mean values of each metric were calculated across all complete intervals registered within each epoch. Mean values of these Epoch means across subjects were calculated for each condition. Distributions for SYNWIN metrics were viewed via boxplots, means, and SDs in exploratory data analysis to illustrate the three-way study design with particular emphasis on testing three questions: 1) were cognitive effects greater in RD vs. gradual ascent; 2) were performance differences evident across "100% O_2" flights where no hypoxia occurred; and 3) did cognitive impairment linger into recovery?

SYNWIN data recorded in the "air" and "100% O_2" conditions were considered separately, with an emphasis on the former, recognizing after exploratory analysis that expected cognitive effects were largely negligible in "100% O_2" conditions. For SYNWIN analyses, Epoch #2 was considered the baseline condition—the best performance subjects could achieve—because our prior experience with this battery[5] indicated that subjects typically settle down to maximal performance after performing for several minutes, and exploratory analyses indicated this occurred in both "air" and "100% O_2" conditions. As with physiological metrics, Epoch #3A was used to represent subjects' cognitive performance throughout ascent and altitude exposure. Analyses comprised two-way, within-subjects 2 × 3 ANOVAs of flights in the "air" condition, using ascent rate (RD vs. gradual) and Epoch (Epoch #2 baseline vs. #3A ascent/altitude vs. #4 recovery) as independent factors. Two-tailed LSD contrasts ($\alpha = 0.05$) were performed to assess differences between baseline Epoch #2 vs. ascent/altitude Epoch #3A for each ascent rate, between baseline Epoch #2 vs. recovery Epoch #4 for each ascent rate, and for means recorded during ascent/altitude (#3A) exposure in the two ascent rate conditions (RD vs. gradual).

Physiological and cognitive data were configured using R and analyzed using SPSS Version 19. Metrics were tested for normality using the Kolmogorov-Smirnov test; those departing from normality were analyzed using the nonparametric Friedman test. Because Friedman tests do not support factorial analysis, these were effectively one-way analyses to identify differences across epochs for each ascent rate. If effects were identified in a metric showing nonnormality, Wilcoxon signed-rank tests were used to characterize them according to ascent-plus-altitude vs. baseline and recovery vs. baseline contrasts. If a metric exhibited non-sphericity in parametric testing, Greenhouse-Geisser correction was applied to the degrees of freedom.

EEG data were recorded from 19 sites on the scalp according to the international 10/20 system[18] using a Mitsar-201 amplifier and an electrode cap (Electro-Cap International, Eaton, OH) referenced to linked earlobes (A1/A2). The sampling rate was 250 Hz. Amplified EEG signals were acquired using WinEEG Advanced software (MITSAR, St. Petersburg, Russia), and processed and analyzed using FieldTrip.[23] Data were first segmented into 2-s intervals. After trial intervals were created, data were high-pass filtered at 0.5 Hz and low-pass filtered at 50 Hz. Each trial interval was assigned to epochs throughout the flight including the baseline GLP (#1) and pre-breathe (#2) epochs, altitude exposure from arrival at 7620 m until exposure termination (Epoch #3), and recovery (#4). Next, independent components analysis was performed on the time-separated data and eye blink and lateral eye movement components were removed for every participant. After independent components analysis, EEG waveforms from frontal electrodes (i.e., Fp1, Fp2) were visually inspected to identify voltage fluctuations typical of gross motor movements (amplitude > 100 μV). Trials containing these types of artifacts were rejected. A frequency analysis was then conducted using a fast Fourier transform utilizing a single Hanning taper for 1–30 Hz.[26] EEG spectra were then further subdivided into the conventional frequency bands Delta (1–3 Hz), Theta (4–7 Hz), Alpha (8–13 Hz), and Beta (15–30 Hz).

A variety of EEG signal analyses were performed. In the interest of brevity, here we report only on a subset of these, namely parametric condition comparisons performed on power spectra recorded across key groups of electrodes that were considered in conjunction. Four a priori selected groups of electrodes were examined in specific frequency bands, based on previous work identifying neural generators for each band.[19,33] We examined Midline Delta activity (1–3 Hz at Fz, Cz, and Pz), Midline Theta activity (4–7 Hz at Fz, Cz, and Pz), Posterior Alpha activity (8–13 Hz at O1 and O2), and Central Beta activity (15–30 Hz at C3, Cz, and C4).

Following exploratory data analysis to plot the electrode groups' power characteristics throughout the flight, repeated-measures ANOVAs were performed on mean spectral power values recorded for each region of interest and corresponding frequency band in Epochs GLP (#1), pre-breathe (#2), altitude (#3, which did not include ascent), and recovery (#4), according to a 2 (ascent rate) × 2 (breathing gas) design. Contrasts identifying power differences based on ascent rate or breathing gas were noted. Note the structural differences between this

analysis and those used for the physiological and cognitive metrics; this was necessitated by the addition of anatomic location as an independent factor resulting in a more complex EEG data configuration (i.e., a four-way design). Also note the distinction between altitude Epoch #3 used in EEG analyses and ascent/altitude Epoch #3A as employed in physiology and cognitive analyses. Epoch #3 was employed in EEG analyses because physical conditions remained fixed as in the other epochs, and because Epoch #3A would have included the neurophysiological response to the countdown and loud RD ascent, which would have produced a signal artifact.

RESULTS

Termination times, representing how long the subject could tolerate the exposure functionally, were recorded extending from the departure from 2743 m until a termination criterion occurred. This could include completion of 10 min at 7620 m in the absence of any physiological or behavioral criterion. Exposures lasting the full duration in gradual flights (13 min 12 s) were reassigned a termination time of 10 min for comparison to equivalent RD flights in which the subject completed the entire altitude exposure. All flights conducted in "100% O_2" conditions lasted full duration. Although certain subjects proved capable of completing 10 min breathing 21% O_2 at 7620 m, 75% of "air" flights ended early, with a mean termination time of 6 min 44 s (SD = 2 min 14 s, range = 4 min 0 s to 10 min 0 s) after gradual ascent and 6 min 1 s (SD = 3 min 8 s, range = 2 min 6 s to 10 min 0 s) after RD. Parametric analyses were not performed on termination times because criteria included both subjective (judged responsiveness and symptoms) and objective (low $S_pO_2/P_{et}O_2$) indicators.

Fig. 3 depicts distributions recorded for selected physiology metrics across Epochs #1, #3A, and #4. Data acquisition issues emerged in the recording of respiration data for two subjects,

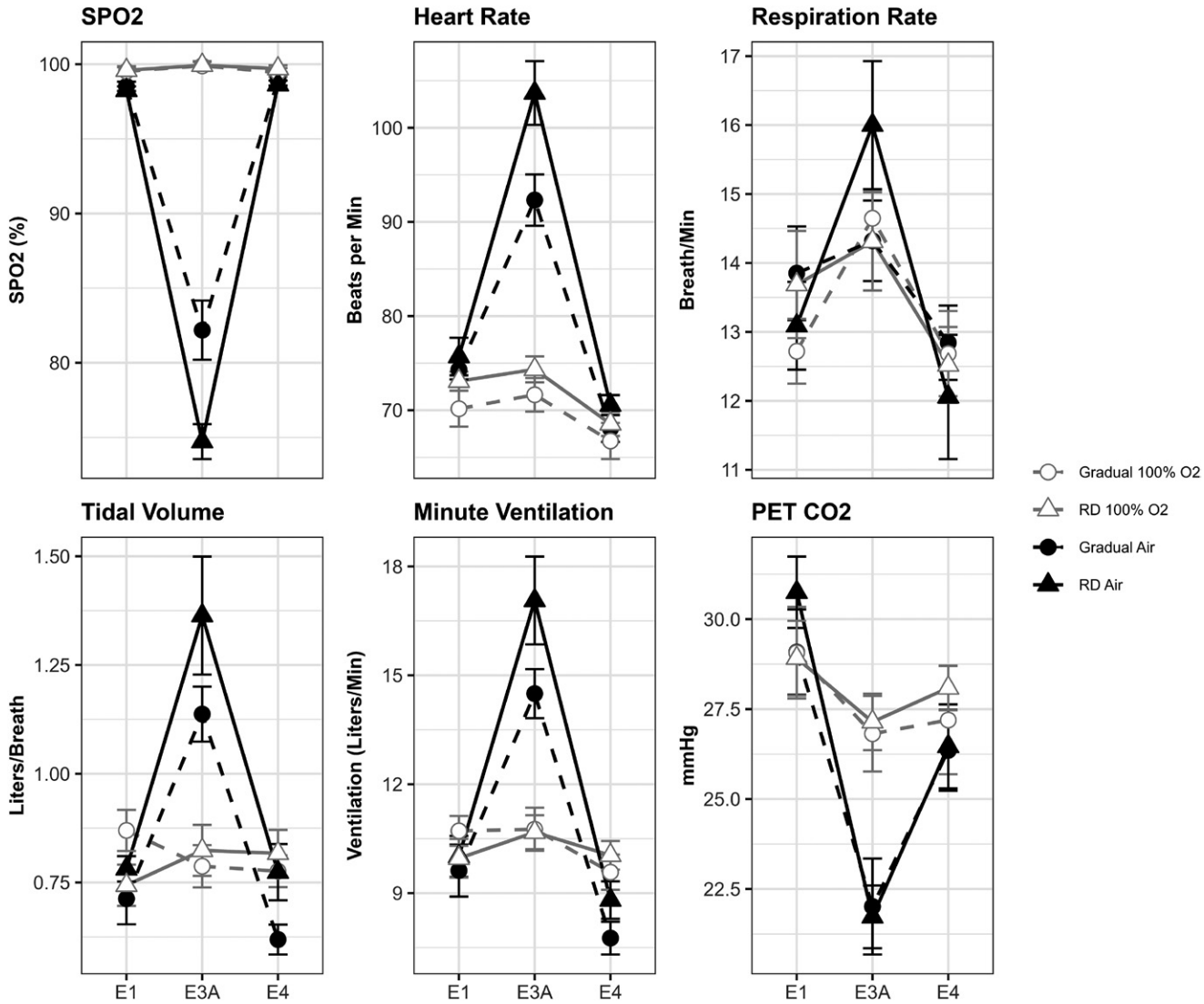

Fig. 3. Physiological metrics recorded across altitude Epochs #1, #3A and #4 for each of four flight conditions (Epoch #2 not displayed because respiration data were not available during pre-breathe). Error bars represent standard error of the mean in each epoch. Darker lines represent "air" flights on which hypoxic performance analyses were performed.

Table I. Analyses of Physiological Metrics in Hypoxic "Air" Conditions.

	EPOCH		ASCENT RATE		EPOCH x ASCENT RATE	
DEPENDENT VARIABLE (DV)	***F* RATIO**	***P*-VALUE**	***F* RATIO**	***P*-VALUE**	***F* RATIO**	***P*-VALUE**
O_2 Saturation (S_pO_2)	**F (1.03, 11.36) = 158.86**	**<0.001**	**F (1, 11) = 23.09**	**0.001**	**F (1.06, 11.63) = 19.03**	**0.001**
Heart Rate (HR)	**F (1.28, 14.03) = 80.77**	**<0.001**	**F (1, 11) = 5.57**	**0.038**	**F (1.20, 13.23) = 7.18**	**0.015**
Respiration Rate (f)	**F (2, 18) = 5.82**	**0.011**	F (1, 9) = 0.002	0.961	F (1.24, 11.18) = 3.80	0.071
Tidal Volume (V_T)	**F (1.12, 10.10) = 21.12**	**0.001**	**F (1, 9) = 7.32**	**0.024**	F (1.24, 11.16) = 0.84	0.405
Minute Ventilation ($\dot{V}_E$)	**F (1.16, 10.48) = 34.73**	**<0.001**	F (1, 9) = 4.35	0.067	F (2, 18) = 1.90	0.179
End Tidal O_2 PP ($P_{et}O_2$)	**F (2, 18) = 320.78**	**< 0.001**	**F (1, 9) = 5.17**	**0.049**	F (2, 18) = 1.58	0.234
End Tidal CO_2 PP ($P_{et}CO_2$)	**F (2, 18) = 24.51**	**< 0.001**	F (1, 9) = 0.28	0.612	F (2, 18) = 0.68	0.518

Epochs #1 (baseline), #3A (ascent plus altitude), and #4 (recovery) were considered. $N = 12$ for S_pO_2 and HR; $N = 10$ for respiration metrics. When departures from sphericity were identified, degrees of freedom reflect Greenhouse-Geisser correction. All comparisons, tests, and contrasts where $P < 0.05$ are bolded.

resulting in an *N* of only 10 for these metrics. Exploratory analyses indicated that in "100% O_2" flights, altitude exposure imposed no significant deviations from Baseline values for most physiological and respiratory metrics including S_pO_2 (N = 12), f, V_T, $\dot{V}_E$, and $P_{et}CO_2$, and for this reason analyses are reported for the hypoxic "air" conditions only. $P_{et}O_2$ levels did sink below baseline during ascent in "100% O_2" flights, but this is likely a result of lower P_IO_2 due to decreased ambient pressure, not an indicator of hypoxia. Mean HR was observed to decrease from baseline levels in the recovery epoch of "100% O_2" flights.

In the independent analysis of physiology metrics in "air" conditions (represented by the darker lines in Fig. 3), altitude ascent imposed significant changes across the three epochs considered (#1 vs. #3A vs. #4). Effects were identified in repeated-measures ANOVAs of metrics including S_pO_2, HR, f, V_T, $\dot{V}_E$, $P_{et}O_2$, and $P_{et}CO_2$ (**Tables I** and **II**). The physiological hypobaric altitude response embodied declines in O_2 saturation and end-tidal partial pressures of O_2 and CO_2 during exposure, coupled with increases in heart rate, respiration rate, inspired volume, and ventilation. Among these metrics, S_pO_2 and HR showed interaction whereby RD imposed greater changes than gradual ascent.

Post hoc contrasts identified decreased S_pO_2, $P_{et}O_2$, and $P_{et}CO_2$ in Epochs #3A vs. #1 and increases in HR, f, V_T, and $\dot{V}_E$ across the same epochs. Differences between means recorded in Epochs #4 vs. #1 were identified for HR, $\dot{V}_E$, and $P_{et}CO_2$, indicating suppression of all three indices during recovery relative to baseline conditions. Contrasts identified greater decreases in S_pO_2 during Epoch #3A after RD [mean S_pO_2 = 74.7 (SD = 4.7)] vs. gradual ascent [mean S_pO_2 = 82.2 (SD = 7.7)], coupled with greater increases in HR after RD [mean = 103.7 (SD = 14.2)] vs. gradual ascent [mean = 92.3 (SD = 9.7)].

Fig. 4 depicts distributions recorded for selected SYNWIN metrics across epochs in the four flight conditions. Since ascent did not impose significant deviations from baseline (Epoch #2) values in "100% O_2" conditions for most SYNWIN metrics (the only exceptions were a decrease in mathematics score and an increase in auditory dwell time and auditory RT Correct), findings are presented for hypoxic "air" conditions only. As shown in Fig. 4, the distribution of SYNWIN scores for the most part overlapped across epochs during the "100% O_2" conditions.

Two subjects failed to deliver any correct responses during Epoch #3A in at least one "air" flight, so they were omitted from the analysis of mathematics RT (Correct) data. These subjects were retained in mathematics score and dwell time analyses

Table II. Post Hoc Comparisons: Physiological Metrics in Hypoxic "Air" Conditions.

		COMBINED			GRADUAL			RD		
DV POST HOC	**CONTRAST**	**M**	**SD**	***P*-VALUE**	**M**	**SD**	***P*-VALUE**	**M**	**SD**	***P*-VALUE**
O_2 Saturation (S_pO_2)	**(#3A - #1)**	**−19.93**	**5.38**	**<0.001**	**−16.33**	**7.42**	**<0.001**	**−23.53**	**4.3**	**<0.001**
	(#4 - #1)	0.40	0.84	0.127	0.43	1.06	0.188	0.38	0.96	0.202
Heart Rate (HR)	**(#3A - #1)**	**23.00**	**10.42**	**<0.001**	**18.02**	**9.19**	**<0.001**	**27.99**	**14.68**	**<0.001**
	(#4 - #1)	**−5.70**	**4.49**	**0.001**	**−6.23**	**5.31**	**0.002**	**−5.16**	**4.99**	**0.004**
Respiration Rate (f)	**(#3A - #1)**	**1.69**	**2.31**	**0.046**						
	(#4 - #1)	−1.02	1.93	0.129						
Tidal Volume (V_T)	**(#3A - #1)**	**0.50**	**0.38**	**0.002**						
	(#4 - #1)	−0.05	0.12	0.198						
Minute Ventilation ($\dot{V}_E$)	**(#3A - #1)**	**5.96**	**3.87**	**0.001**						
	(#4 - #1)	**−1.53**	**1.37**	**0.006**						
End Tidal O_2 PP ($P_{et}O_2$)	**(#3A - #1)**	**−71.41**	**10.42**	**<0.001**						
	(#4 - #1)	0.69	8.96	0.813						
End Tidal CO_2 PP ($P_{et}CO_2$)	**(#3A - #1)**	**−8.05**	**3.55**	**<0.001**						
	(#4 - #1)	**−3.51**	**3.01**	**0.005**						
O_2 Saturation (S_pO_2)	**(#3A: RD-Gradual)**	**−7.47**	**5.56**	**0.001**						
Heart Rate (HR)	**(#3A: RD-Gradual)**	**11.37**	**12.37**	**0.009**						

Physiology post hoc results (two-tailed LSD; α = 0.05) are listed comparing Epochs #3A vs. #1; comparing #4 vs. #1; and comparing RD vs. gradual ascent within Epoch #3A. Contrasts are broken out for S_pO_2 and HR because these metrics showed (Epoch x ascent rate) interaction. M = mean; SD = standard deviation. All comparisons, tests, and contrasts where $P < 0.05$ are bolded.

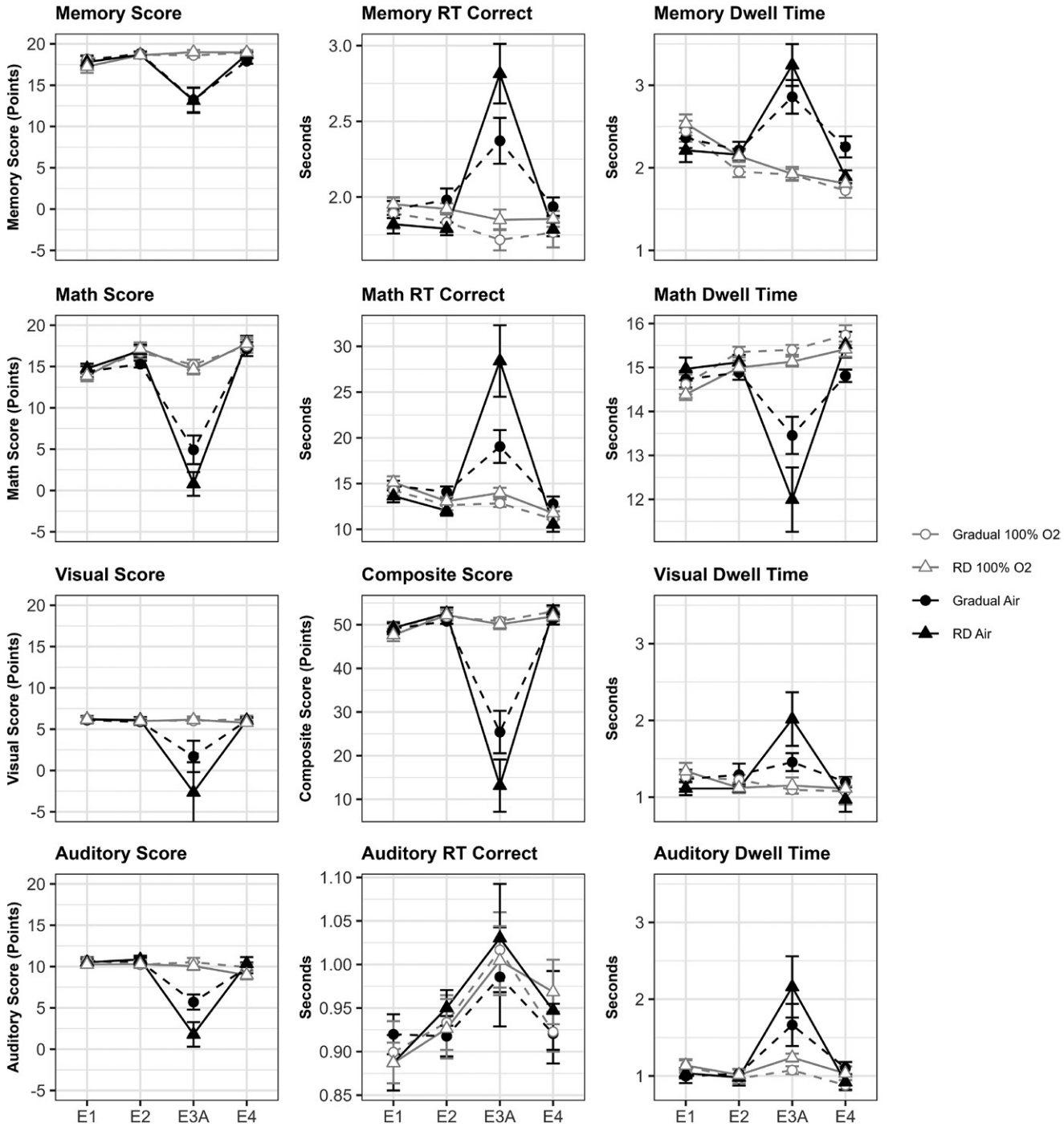

Fig. 4. SYNWIN metrics recorded across altitude epochs for each flight condition. Error bars represent standard error of the mean in each epoch. Darker lines represent "air" flights on which hypoxic performance analyses were performed. Analyses included only Epochs #2 (considered baseline for SYNWIN performance), #3A, and #4.

since they were playing the game even if they were not scoring on this task. For all other SYNWIN metrics, $N = 12$.

Altitude ascent imposed cognitive effects across the course of flights in the "air" condition, including Epochs #2, #3A, and #4. Main effects of epoch were identified for all SYNWIN metrics save auditory RT (**Table III**). In all four tasks and in the composite summary, scores deteriorated during Epoch #3A and rebounded in recovery, where no residual impairment was observed for any task. Interactions emerged for composite score, memory RT (Correct), mathematics score and RT (Correct), and auditory score, indicating that ascent imposed greater impairment in RD vs. gradual conditions.

Post hoc contrasts were consistent with the above findings, identifying decreased composite, memory, mathematics, and auditory scores in Epochs #3A vs. #2, coupled with increased mathematics RT and memory RT (**Table IV**). No differences

Table III. Analyses of SYNWIN Cognitive Scores in Hypoxic "Air" Conditions (Parametric).

	EPOCH		ASCENT RATE		EPOCH x ASCENT RATE	
DEPENDENT VARIABLE (DV)	***F* RATIO**	***P*-VALUE**	***F* RATIO**	***P*-VALUE**	***F* RATIO**	***P*-VALUE**
Composite Score	**F (1.02, 11.21) = 34.95**	**<0.001**	F (1,11) = 1.93	0.192	**F (1.25, 13.75) = 7.79**	**0.011**
Memory Score	**F (1.04, 11.42) = 17.29**	**0.001**	F (1,11) = 0.06	0.806	F (1.29, 14.22) = 0.31	0.641
Memory RT Correct	**F (1.24, 13.60) = 18.85**	**<0.001**	F (1,11) = 0.17	0.687	**F (2, 22) = 10.77**	**0.001**
Memory Dwell Time	**F (1.19, 13.05) = 20.27**	**<0.001**	F (1,11) = 0.01	0.916	**F (2, 22) = 3.48**	**0.049**
Math Score	**F (1.25, 13.71) = 58.05**	**<0.001**	F (1,11) = 0.54	0.476	**F (2, 22) = 10.73**	**0.001**
Math RT Correct	**F (1.04, 9.32) = 16.79**	**0.002**	F (1,11) = 4.53	0.062	**F (1.03, 9.29) = 9.49**	**0.012**
Auditory Score	**F (1.23, 13.50) = 21.87**	**<0.001**	F (1,11) = 4.27	0.063	**F (1.23, 13.56) = 6.22**	**0.021**
Auditory RT Correct	F (1.37, 15.04) = 1.25	0.299	F (1,11) = 0.73	0.411	F (2, 22) = 0.04	0.963
Auditory Dwell Time	**F (1.03, 11.37) = 5.67**	**0.035**	F (1,11) = 1.04	0.330	**F (1.27, 14.01) = 5.04**	**0.034**

Epochs #2 (baseline), #3A (ascent plus altitude), and #4 (recovery) were considered. Epoch #2 was considered baseline (representing maximum performance) because participants reliably improved after performing SYNWIN for several minutes in GLP Epoch #1. $N = 12$ for all metrics save mathematics RT, for which $N = 10$ because two subjects delivered no correct responses when hypoxic. When departures from sphericity were identified, degrees of freedom reflect Greenhouse-Geisser correction. All comparisons, tests, and contrasts where $P < 0.05$ are bolded.

were identified between means recorded in Epochs #4 vs. #2, save a reduction in mathematics RT recorded during recovery. Contrasts identified lower scores (greater impairment) during hypoxic RD vs. gradual ascents for composite, mathematics, and auditory scores, coupled with greater increases in mathematics and memory RT.

Departures from normality were observed in three SYNWIN metrics (**Table V**). In visual monitoring, hypoxia increased subjects' tendency to overlook the meter's expiration (a lapse) and invoke progressive and occasionally severe time penalties, which yielded extreme negative (e.g., >3 SDs from the mean) outliers in visual monitoring score. The mathematics dwell time and visual dwell time metrics departed from normality in a manner that suggested individual differences in cognitive style: certain subjects appeared to shy from expending time on mathematics, while the converse tendency appeared in visual monitoring, with some individuals retreating to this relatively less demanding task. For these metrics, the respective nonparametric tests indicated significant effects of epoch, with lower visual monitoring scores and mathematics dwell times during Epoch #3A in both "gradual air" and "RD air" conditions, and higher visual dwell times during Epoch #3A in "RD air" conditions. These one-way nonparametric tests did not accommodate direct tests of interaction between ascent rate and breathing gas.

The profile of dwell times across tasks indicated priority for the mathematics task: subjects spent most of their time in the upper right quadrant. Notably, ascent in "air" flights induced a migration away from this zone of the workstation, whereby subjects increased time spent performing memory, auditory,

Table IV. Post Hoc Comparisons: SYNWIN Cognitive Scores in Hypoxic "Air" Conditions (Parametric).

		COMBINED			GRADUAL			RD		
DV POST HOC	**CONTRAST**	**M**	**SD**	***P*-VALUE**	**M**	**SD**	***P*-VALUE**	**M**	**SD**	***P*-VALUE**
Composite Score	**(#3A - #2)**	**−32.42**	**19.22**	**<0.001**	**−25.38**	**17.36**	**<0.001**	**−39.46**	**23.77**	**<0.001**
	(#4 - #2)	0.52	2.16	0.422	0.53	3.45	0.604	0.51	4.67	0.713
Memory Score	**(#3A - #2)**	**−5.57**	**4.6**	**0.002**						
	(#4 - #2)	−0.43	0.79	0.085						
Memory RT Correct	**(#3A - #2)**	**0.71**	**0.58**	**0.001**	**0.39**	**0.6**	**0.046**	**1.02**	**0.7**	**<0.001**
	(#4 - #2)	−0.02	0.23	0.716	−0.04	0.35	0.672	−0.004	0.16	0.925
Memory Dwell Time	**(#3A - #2)**	**0.87**	**0.64**	**0.001**	**0.64**	**0.79**	**0.016**	**1.09**	**0.94**	**0.002**
	(#4 - #2)	−0.11	0.26	0.156	0.04	0.42	0.753	−0.27	0.43	0.056
Math Score	**(#3A - #2)**	**−13.25**	**5.79**	**<0.001**	**−10.38**	**6.29**	**<0.001**	**−16.12**	**6.17**	**<0.001**
	(#4 - #2)	1.41	2.54	0.243	1.82	3.1	0.067	1.00	3.23	0.306
Math RT Correct	**(#3A - #2)**	**10.28**	**8.27**	**0.003**	**4.97**	**5.35**	**0.008**	**16.22**	**13.69**	**0.005**
	(#4 - #2)	**−1.22**	**1.32**	**0.017**	**−1.31**	**1.96**	**0.041**	**−1.48**	**1.59**	**0.008**
Auditory Score	**(#3A - #2)**	**−6.99**	**4.65**	**<0.001**	**−4.9**	**3.68**	**0.001**	**−9.07**	**6.27**	**<0.001**
	(#4 - #2)	−0.64	1.86	0.258	−0.77	2.39	0.290	−0.51	2.52	0.495
Auditory Dwell Time	**(#3A - #2)**	**0.91**	**1.34**	**0.039**	0.64	1.08	0.067	**1.18**	**1.68**	**0.034**
	(#4 - #2)	0.01	0.21	0.904	0.07	0.32	0.429	−0.06	0.25	0.419
Composite Score	**(#3A: RD-Gradual)**	**−12.28**	**17.00**	**0.029**						
Memory RT	**(#3A: RD-Gradual)**	**0.44**	**0.61**	**0.028**						
Memory Dwell Time	(#3A: RD-Gradual)	0.39	0.90	0.166						
Math Score	**(#3A: RD-Gradual)**	**−4.13**	**4.24**	**0.006**						
Math RT Correct	**(#3A: RD-Gradual)**	**10.56**	**11.86**	**0.020**						
Auditory Score	**(#3A: RD-Gradual)**	**−3.92**	**3.75**	**0.004**						
Auditory Dwell Time	(#3A: RD-Gradual)	0.50	0.79	0.051						

Cognitive post hoc results (two-tailed LSD; $\alpha = 0.05$) are listed comparing Epochs #3A vs. #2; comparing #4 vs. #2; and comparing RD vs. gradual ascent within Epoch #3A. Contrasts are broken out for metrics where Epoch x ascent rate interaction emerged. M = mean; SD = standard deviation. All comparisons, tests, and contrasts where $P < 0.05$ are bolded.

Table V. Analyses of SYNWIN Cognitive Scores in "Air" Conditions (Nonparametric).

		FRIEDMAN TEST			WILCOXON SIGNED RANK TEST *P*-VALUES	
DEPENDENT VAR.	**ASCENT RATE**	χ^2	*df*	*P*	**(#3A - #2)**	**(#4 - #2)**
Visual Score	Gradual	**11.17**	**2**	**0.004**	**0.01**	0.31
	RD	**10.61**	**2**	**0.005**	**0.01**	0.84
Math Dwell Time	Gradual	**12.67**	**2**	**0.002**	**0.004**	0.64
	RD	**15.17**	**2**	**0.001**	**0.003**	0.21
Visual Dwell Time	Gradual	0.00	2	1.00		
	RD	**6.50**	**2**	**0.04**	**0.01**	0.84

All comparisons, tests, and contrasts where $P < 0.05$ are bolded.

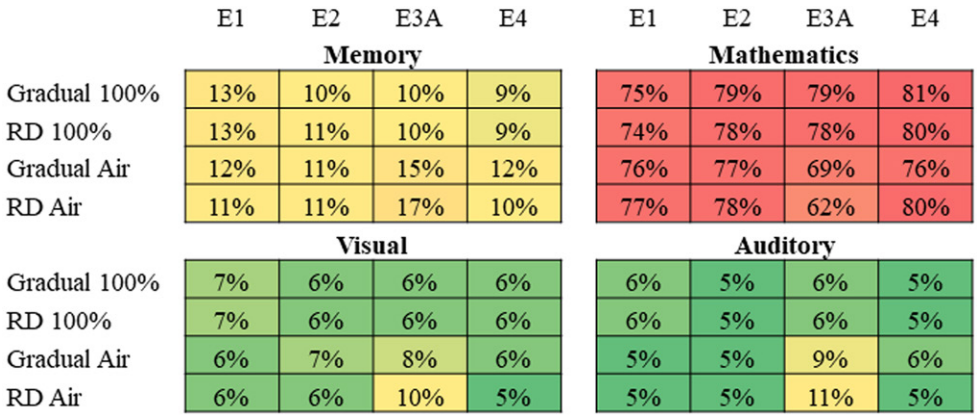

Fig. 5. Dwell time heat-map representation of percent time spent for the four SYNWIN tasks throughout successive epochs. Note migration away from mathematics task during ascent in "air" flights.

and visual monitoring tasks during the progressive onset of hypoxia in Epoch #3A, at the expense of the mathematics task (**Fig. 5**).

EEG analyses included complete sets of signals from nine subjects: two were omitted due to recording issues and one was identified as a statistical outlier for registering >3 SD above group means for spectral power. As described, 2×2 (ascent rate x breathing gas) repeated-measures ANOVAs were conducted for Epochs #1–4 in the frequency bands Delta (1–3 Hz), Theta (4–7 Hz), Alpha (8–13 Hz), and Beta (15–30 Hz) among selected regions of interest. Significant findings were identified only in altitude Epoch #3, where a main effect of breathing gas was identified in two combinations of frequency band and location (**Table VI**, **Fig. 6**). For Midline Delta, spectral power increased with hypoxia onset in both "RD-plus-air" and "gradual-plus-air" conditions compared to "100% O_2" conditions ($P = 0.006$), with no interaction identified. In addition, spectral power increased for Central Beta during the two "air"

Table VI. Analyses of Regional EEG Power Spectra.

		ASCENT RATE		BREATHING GAS		ASCENT RATE x BREATHING GAS	
REGION FREQ.	**EPOCH**	***F* RATIO**	***P*-VALUE**	***F* RATIO**	***P*-VALUE**	***F* RATIO**	***P*-VALUE**
Midline Delta	GLP: Epoch 1	$F(1,8) = 0.41$	0.536	$F(1,8) = 0.31$	0.595	$F(1,8) = 2.34$	0.164
	Pre-Breathe: Epoch 2	$F(1,8) = 0.29$	0.602	$F(1,8) = 0.75$	0.412	$F(1,8) = 1.96$	0.200
	Altitude: Epoch 3	$F(1,8) = 0.05$	0.835	**$F(1,8) = 14.00$**	**0.006**	$F(1,8) = 0.025$	0.879
	Recovery: Epoch 4	$F(1,8) = 0.58$	0.468	$F(1,8) = 0.61$	0.458	$F(1,8) = 3.86$	0.085
Midline Theta	GLP: Epoch 1	$F(1,8) = 0.95$	0.357	$F(1,8) = 0.30$	0.599	$F(1,8) = 0.95$	0.358
	Pre-Breathe: Epoch 2	$F(1,8) = 0.76$	0.410	$F(1,8) = 0.81$	0.395	$F(1,8) = 0.75$	0.411
	Altitude: Epoch 3	$F(1,8) = 1.34$	0.281	$F(1,8) = 5.11$	0.054	$F(1,8) = 1.33$	0.282
	Recovery: Epoch 4	$F(1,8) = 0.93$	0.364	$F(1,8) = 0.07$	0.797	$F(1,8) = 1.00$	0.346
Posterior Alpha	GLP: Epoch 1	$F(1,8) = 0.19$	0.676	$F(1,8) = 0.07$	0.798	$F(1,8) = 0.88$	0.376
	Pre-Breathe: Epoch 2	$F(1,8) = 1.05$	0.336	$F(1,8) = 0.04$	0.854	$F(1,8) = 1.06$	0.334
	Altitude: Epoch 3	$F(1,8) = 1.62$	0.239	$F(1,8) = 4.16$	0.076	$F(1,8) = 2.24$	0.173
	Recovery: Epoch 4	$F(1,8) = 0.20$	0.670	$F(1,8) = 0.01$	0.936	$F(1,8) = 1.67$	0.233
Central Beta	GLP: Epoch 1	$F(1,8) = 1.34$	0.280	$F(1,8) = 1.30$	0.287	$F(1,8) = 0.15$	0.711
	Pre-Breathe: Epoch 2	$F(1,8) < 0.01$	0.995	$F(1,8) = 0.16$	0.701	$F(1,8) = 0.02$	0.884
	Altitude: Epoch 3	$F(1,8) = 2.34$	0.165	**$F(1,8) = 7.27$**	**0.027**	$F(1,8) = 2.68$	0.140
	Recovery: Epoch 4	$F(1,8) = 0.10$	0.761	$F(1,8) = 1.75$	0.223	$F(1,8) = 3.22$	0.110

All comparisons, tests, and contrasts where $P < 0.05$ are bolded.

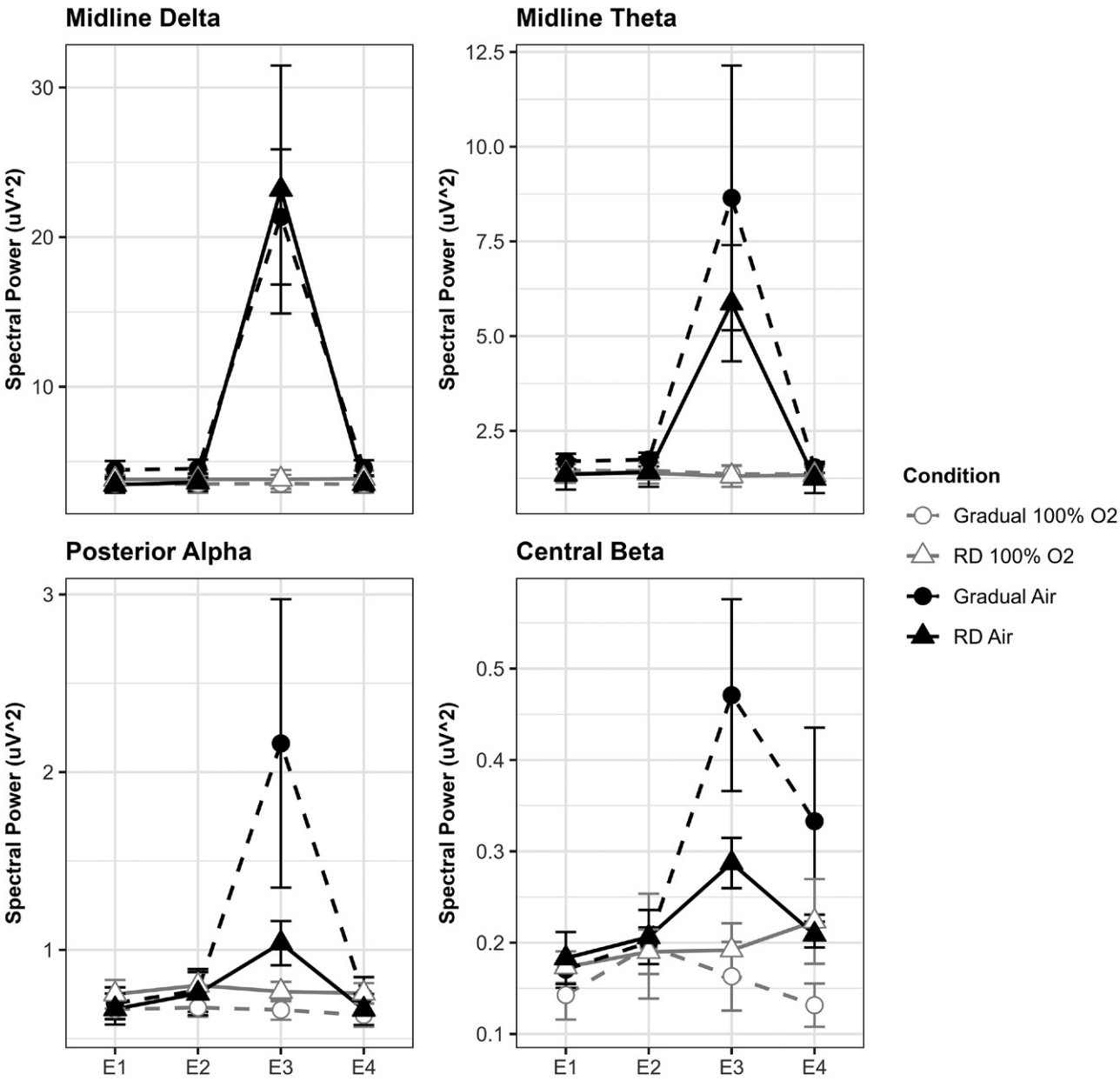

Fig. 6. Regional EEG spectral power bands where effects were identified in Epoch #3, plotted across altitude epochs ($N = 9$). Error bars represent standard error of the mean in each epoch. Darker lines represent "air" flights which included hypoxic conditions at altitude. NB: Epoch #3 differs slightly from #3A (used in analyses described above) in that #3 includes only time spent at 7620 m.

flights as compared to "100% O_2" flights ($P = 0.027$), also with no interaction identified.

DISCUSSION

In the comparison between RD and gradual decompressions, altitude effects that emerged in hypoxia-inducing "air" flights showed differences depending on ascent rate. SYNWIN metrics including composite score, memory RT, mathematics score (a sensitive SYNWIN component for detecting hypoxia[2]) and RT, and auditory score showed greater impairment after RD. Cognitive impairment following hypoxic RD (as indicated via these steeper declines in cognitive accuracy, executive processing, and throughput) was accompanied by greater effects on S_PO_2 and HR, indicating sharper decreases and increases, respectively, for these physiological metrics. In the context of flight operations, this finding is consistent with the conclusions of smaller legacy studies that yielded influential textbook predictions that RD—which is more likely in a compact fighter cockpit than in a voluminous passenger or transport cabin—will inflict greater physiological impact coupled with shorter TUC.[6,13] Notwithstanding this agreement, we note that striking individual differences emerged among our participants, certain of whom lasted much longer breathing air at 7620 m—even after RD—than the 5-min-or-less TUC predictions listed in textbooks and summaries of previous findings.[16,31]

Little evidence emerged that altitude exposure impeded cognitive performance in the absence of hypoxia (see also Aebi et al.[1]): in "100% O_2" flights, subjects for the most part responded as accurately and swiftly during ascent-altitude as in GLP, pre-breathe, and recovery epochs. Similarly, physiological metrics including those responsive to stress were largely immune to ascent in both "100% RD" and "100% gradual" flights despite subjects' knowledge of their imminent, perhaps rapid, excursion to high-altitude conditions (Fig. 3). EEG signals showed a similar lack of power spectrum changes during ascent in the absence of hypoxia.

In "air" flights where altitude-related cognitive impairment was registered, there was no indication that the impairment persisted in recovery; indeed, the only performance difference registered after exposure was a paradoxical decrease in mathematics RT. Although this contrast echoes earlier findings indicating subjects respond more swiftly in certain tasks during[3] or after[4] hypoxia, a definitive explanation for the mean RT decrease is elusive, and it might constitute a random Type I finding. This absence of lingering impairment comprises a lack of what has been called "hypoxia hangover," which has been described in other studies with various degrees of severity,[5,35,36] including none.[10,32] In accounting for this divergence, we note that the different studies employed diverse conditions and tests, and that, even within the SYNWIN battery,[2] different tasks gauge hypoxia effects with different sensitivities. A distinguishing characteristic of the current study is that it employed exposures that, although severe enough to induce physiological effects, were relatively brief compared to exposures in other studies where lingering impairment was reported, which ranged from 10–35 min and beyond.[4,7,28] Here, most hypoxia exposures were shorter than 10 min, and 100% O_2 was administered on descent as a safety measure.

The overall configuration of physiological effects during "air" exposures comprised a broad respiratory and sympathetic response to hypoxic altitude conditions. Effects encompassed decreased peripheral S_pO_2 (more so after RD) and $P_{et}O_2$, increased HR (greater after RD), and a characteristic coupling of elevated ventilation with decreased $P_{et}CO_2$. The hypocapnia embodied in this last process has been linked with cognitive effects that resemble hypoxia symptoms during and after altitude exposure, and researchers have emphasized that hypoxia and hypocapnia effects can occur independently, in combination, or in succession.[31,34,35] In this context, it is notable that administering CO_2 has been claimed to attenuate hypoxia-induced impairment in cognitive tasks and simulated driving.[8,14] These findings leave open the possibility that some of the decline in SYNWIN performance at altitude in "air" flights was mediated by neurocognitive and hemodynamic processes resulting from hyperventilation-induced hypocapnia.[35]

Lack of lingering cognitive effects notwithstanding, three physiological metrics exhibited postexposure changes in recovery relative to baseline epochs. Depressed $P_{et}CO_2$—persistent hypocapnia—represents a slower-recovering (relative to S_pO_2 and $P_{et}O_2$) holdover from altitude exposure which may contribute to the lower HR and $\dot{V}_E$ means recorded during recovery.[37] Slowing in these latter metrics might, alternatively, have resulted from compensatory mechanisms to counter the sympathetic altitude response, in accordance with Laborde et al.'s[21] claim that physiologically stressful events induce vagal recovery activation of the parasympathetic nervous system. We note also that these metrics (like the dynamics of neurocognitive recovery discussed above) could have been influenced by the administration of 100% O_2 on descent or by safety instructions issued by attending physiologists.

The evolution of SYNWIN performance throughout the course of a hypobaric hypoxia excursion yielded striking findings, as did the migration of visual effort allocation evinced by the distribution of cursor dwell times. Whether consciously or not, proficient performers adopted an efficient allocation strategy that prioritized the mathematics task, and this strategy changed with the onset of hypoxia. Whereas the maximum reward from the other three tasks was limited by the timing of the game, subjects appeared to recognize that the only scoring tool they could optimize themselves was mathematics throughput: number of correct sums completed per minute. It is likely that the warm-up effect, whereby scores increased from Epochs #1 to #2, occurred because subjects were developing increased automaticity in performing the other three tasks, especially memory, in which continuing to play yielded greater rote familiarity with the sample set. This progressive automaticity could enable subjects to prioritize Mathematics throughput and maximize scoring. Having established this, we see not only that SYNWIN success is optimized when mathematics is prioritized, but that according to the heat map in Fig. 5, this strategy weakens in Epoch #3A of "air" flights: in the hypoxia-impaired subject, mathematics dwell time declines and the opportunistic edge of efficiency gives way to a "satisficing" strategy that partially retreats to alternative tasks that can be serviced more automatically.

We now consider the EEG effects that were identified during the altitude Epoch of hypoxia-inducing "air" flights as compared to 100% O_2. First, and consistent with previous work,[20] we recorded increased Delta power at altitude when subjects were breathing air. Delta power is typically associated with decreased alertness and dominates the EEG signal when individuals are in deep sleep. Here, the increased Delta power in awake subjects suggests that alertness was impaired during hypoxia. Second, we recorded increased Beta power at altitude when subjects were breathing air. Registering Beta power across central electrodes indicates motor activation; given the nature of the SYNWIN task, this suggests that when individuals were hypoxic, they were exerting increased motor control effort to maintain performance.

Our overall configuration of EEG findings is largely consistent with earlier findings in which hypoxia increased spectral activity in Theta,[20,24,25] Delta,[20] and Alpha[25] bands, and one finding that normobaric hypoxia increased power across multiple bands.[29] Echoing the Kraaier study,[20] "100% O_2" flights saw a relative lack of EEG spectral response to hypobaric ascent without hypoxia. Our findings offer some confirmation for prior findings indicating that hypoxia increases

activity in slow-wave EEG bands—in this case, as subjects strive to remain alert while performing workstation tasks. Unlike the effects observed with oximetry, respiration, and cognitive metrics, the spectral findings manifested similarly at both environmental onset rates. Although including more subjects in the manipulation might have yielded greater sensitivity to distinguish between RD and gradual ascent, it seems clear that both hypoxic decompressions induced slow-wave activity whose characteristics at least diagnostically resembled those of imminent somnolence—a potential threat to pilot performance.

The study included some potential limitations. Although a male–female balance was sought in subject recruitment, during the study only one female subject volunteered. While the experiment met its objective of increasing statistical power from that of legacy studies' physiological and cognitive comparisons of RD vs. gradual ascent, this advance was limited somewhat in the comparison of EEG metrics by data issues that reduced available *N*. Finally, for safety reasons, the technical crew were not blind to the conditions presented. Although investigators were asked never to discuss conditions with subjects, it is possible that experimenter cues were conveyed unintentionally or that an attentive subject could have deduced conditions expected in later flights.

This study addressed the empirical questions posed: in the hypobaric conditions presented here, RD impaired cognitive performance more than gradual ascent in hypoxic exposures; hypobaria did not comprehensively impair workstation performance in the absence of hypoxia; and altitude-related cognitive impairment did not linger into recovery. With the onset of hypoxia and the attendant hypocapnia, a shift was identified in subjects' cognitive strategy whereby efficient task allocation for maximum throughput gave way to a "satisficing" strategy allocating more effort to easier, more automated task components. EEG spectral analysis yielded some evidence that hypoxia increased regional slow-wave activity.

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