

The Effect of Microgravity on the Human Voice, Phonation- A Single Case Study

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Abstract

This study investigates the physiological and acoustic alterations in the human vocal apparatus induced by exposure to microgravity. Given the expansion of commercial spaceflight and long-duration missions, understanding vocalization mechanics under the circumstances of microgravity is essential for ensuring effective communication and monitoring astronaut well-being. We conducted a comprehensive, multi-modal, single-case study involving one male flying astronaut during a mission to the International Space Station. Assessments were performed across three phases: Pre-flight, In-flight, and Post-flight. A backup astronaut and a matched healthy control population served as reference groups. Data acquisition included EGG and acoustic analysis (fundamental frequency [f_0], jitter, cepstral peak prominence [CPP]), and the contact quotient [CQ]), and standardized questionnaires. Interrupted time-series analyses revealed significant phase-dependent shifts in phonatory behaviour. During microgravity exposure, there was a marked reduction in phonatory stability, characterized by a significant decrease in CPP (approximately - 27%) and CQ (approximately - 7.3%), alongside a significant increase in jitter (approximately + 51.8%). While descriptive data showed a moderate increase in f_0 (+ 12.0%), the temporal pattern was complex. Principal component analysis confirmed these changes formed a coordinated multivariate pattern. Questionnaire results indicated an increase in self-reported interest and vocal tract discomfort during flight, but analysis suggested these as covariates, and not causal factors. Vocal handicap scores remained subclinical. Our results suggest, that spaceflight induces measurable alterations in human phonation, likely resulting from a combination of systemic fluid shifts, altered respiratory mechanics, and sensorimotor recalibration. While these changes are subclinical, the reduction in vocal stability underscores the need for continued monitoring and the development of targeted countermeasures to maintain optimal communication ability of the astronauts during prolonged spaceflight. Besides vocal changes may serve as a way to monitor the health status of the astronauts.

Introduction

The challenges of long-duration space missions and, due to the commercialisation of spaceflight, the rapidly expanding market for short-term space trip necessitates a comprehensive understanding of all physiological adaptations experienced by astronauts, including alterations in vocalization mechanics.

Speech serves as the primary mode of interpersonal communication among humans, and currently the only continuous channel during a spaceflight. The human speech not only mediate the semantic content of spoken words but also critical insights into an individual's health status¹⁻⁵, emotional state⁶⁻⁸, and cognitive function^{9,10}. This paper examines the physiological and acoustic alterations observed in the human vocal apparatus when exposed to spaceflight. Understanding these changes is crucial for ensuring effective communication and a possible way to monitoring astronaut well-being during prolonged missions beyond low-Earth orbit and during the adaptation process through short-duration missions.

Spaceflight induces a variety of physiological and pathological adaptations in the human body, primarily resulting from prolonged exposure to microgravity. These changes range from systemic fluid redistribution¹¹, and musculoskeletal degradation¹² to alterations in fine motor control^{13,14}, brain function¹⁵, vestibular system function¹⁶, and vision¹⁷. Upon entering microgravity, the human body undergoes a significant "fluid shift" where bodily fluids move toward the head and upper body part¹⁸. Respiratory mechanics are also altered in several ways. Fluid shift increases blood and fluid volume in the thorax and apices of the lungs, changing lung mechanics^{19,20}. The tidal volume decreases, respiratory rate increases and alveolar ventilation decreases slightly²⁰. The contribution of abdominal muscles increases, shifting toward abdominal breathing^{21,22}. Vital capacity transiently decreases, though it typically returns to baseline after several days¹⁹. These changes may affect the regulation of subglottal pressure that can alter voice characteristics^{23–26}. The fluid-shifts can lead to a facial oedema²⁷ and may affect the vibratory characteristics of vocal folds and the resonance of the upper respiratory tract. In addition to microgravity, the partial pressure of CO₂ aboard the International Space Station (ISS) averages around 4 mmHg—substantially higher than the typical 0.3 mmHg on Earth²⁸. These elevated levels have been associated with an increased incidence of headaches among crew members²⁸. Although hypercapnia may influence voluntary ventilation patterns²⁹, laryngeal motor control remains unaltered³⁰. Recent research revealed that the effects of microgravity extend to fine motor skills, specifically the complex movements required for speech production. Studies of astronauts before and after space missions show a more distal than usual position of the articulators (tongue, lower jaw)¹³. These physiological adjustments manifest as measurable changes in speech, including shifts in fundamental frequency (f_0) and formant frequencies³¹.

Analysis of voice pitch (f_0) has shown a correlation with effort during mission-relevant tasks, such as hand-controlled docking maneuvers or cognitive tests²⁴. In dry immersion experiments f_0 has shown a decrease in the case of female operators in the second day, after an immediate increase³². In conclusion, spaceflight triggers comprehensive physiological adaptations in respiration, vocal tract posture and sensorimotor alterations. Furthermore, the interplay between laryngeal muscle activation and fluid-structure interaction within the glottis³³, may undergo disruption in a microgravity environment¹³. Despite the current substantial understanding regarding alterations in vocal characteristics, to our knowledge no previous systematic, multimodal, and controlled study has investigated changes in vocal characteristics during spaceflight. To address this research gap, we conducted pre-, in- and post-flight vocal assessments, accompanied by concurrent electroglottographic measurements, on the primary astronaut, a backup astronaut and for reference, a control population of healthy male individuals. We hypothesized that vocal characteristics would change during microgravity exposure, alterations that could be confirmed by electroglottographic measurements. To determine the contributions of mental or emotional factors, we also administered questionnaires.

Materials and methods

Participants

The study involved one flying astronaut (mission duration: 20 days) serving as the primary experimental subject and one backup astronaut acting as the control participant. The astronaut underwent vocal assessments before, during, and after a microgravity exposure, while the backup astronaut served as a control to account for baseline variability and non-microgravity related factors. Both participants were male (aged between 30–45 years), with no reported history of vocal, speech, language, or hearing disorders, or any neurological or mental illnesses. Before and after the mission a laryngostroboscopic examination was performed to rule out any organic disorders. For reference values we measured a matched population of 18 male speakers with no reported history of vocal, speech, language, or hearing disorders, or of neurological or mental illness, aged 19–43 years (mean age: 30,7). The research protocol was designed and conducted in accordance with the regulations and laws of the USA and Hungary, and with the Declaration of Helsinki, and was approved by the National Aeronautics and Space Administration (NASA, FWA Number: 00019876), and the National Center for Public Health and Pharmacy, Hungary (file number: BM/24434-1/2025). All participants provided informed consent prior to their involvement in the study.

Experimental protocol

The experimental protocol encompassed a series of vocal tasks aimed at capturing the vocal fine control, resonance and articulatory alterations induced by microgravity exposure.

The experimental protocol comprised sustained phonation of the vowels /æ/, /i/, and /u/ in a normal style at habitual speaking pitch and loudness for 4 s, as well as /a/ in crescendo and glissando modes, alongside measurement of maximum phonation time (MPT) with the vowel /o/. Each task was repeated three times. Participants additionally read a short story aloud (“The North Wind and the Sun”) in their native language, sang a folk song (“Spring Wind Floods the Water”) also in their native language starting from a predetermined pitch, and performed a pitch-matching task. The vocal ranges for the song and pitch-matching task were adjusted to the astronaut's comfortable singing range. All recordings were conducted in a sound-attenuated environment to minimize extraneous noise and ensure high-fidelity audio capture for subsequent acoustic analysis.

To assess possible vocal tract discomfort and emotional condition, standardized questionnaires were administered, including the Vocal Handicap Index (VHI)³⁴, the Vocal Tract Discomfort Scale (VTDS)^{35,36} and the Differential Emotions Scale (DES) by Izard^{37–39}. These questionnaires provided subjective data that complemented the objective acoustic and physiological measures, giving a comprehensive view of participants' vocal health and psychological state during the study—factors that might affect vocal performance independently of microgravity.

All sessions followed the same protocol. Sessions were conducted for the astronaut before spaceflight (Phase A, 4 sessions, Launch (L)-30, L-25, L-24, and L-20 days;), during spaceflight (Phase B, 3 sessions, Flight Day (FD)7, FD9, and FD16;), and after spaceflight (Phase C, 3 sessions, Return (R) + 3, R + 4, and R

+ 7.) for a total of 10 sessions, and for the control subject matched L-29, L-25, L-24, L-20, FD9, FD17, R + 3, R + 5, and R + 6 days (9 sessions). In the case of the flying astronaut FD 9 was a repeated session due to technical issues. This is the reason why the control subject had only 9 measurements. Healthy control speakers had one session using the same protocol.

Although the overall recording protocol comprised a broader set of speech and voice tasks, the present analysis was restricted to the subset of sustained vowel recordings and their corresponding acoustic and electroglottographic outcomes. This focused approach was chosen to enable detailed investigation of microgravity-related changes in phonatory behaviour. Consequently, the subsequent sections report only the acquisition and analytical procedures relevant to these selected measures.

Data acquisition

Electroglottography (EGG) was applied as an objective way to measure vocal fold phonatory function, independent of possible background noise^{40–42} using the EGG-D200 Electroglottography System (Laryngograph Ltd., London, UK), supplied with a Røde *Lavalier GO* microphone (RØDE Microphones, Sydney, Australia, <https://www.ode.com>) with the SpeechStudio 5.4.0 software (Laryngograph Ltd London, UK).

Before the sessions the EGG equipment was calibrated according to the instruction manual. These measurements establish a robust basis for delineating microgravity-induced alterations in laryngeal function, including potential compensatory mechanisms that astronauts may adopt.

The subjects were instructed beforehand on the experimental protocol, including the specific vocal tasks, the usage of the devices, and the expected duration of each activity, to minimize variability arising from unfamiliarity with the procedures.

Due to technical issues, the Cepstral Peak Prominence (CPP) of the first session of Phase B (FD7) was not comparable with the other sessions and the questionnaires were not administered for the second session of Phase B (FD9) in the case of the flying astronaut (as permission was granted to repeat only the technically problematic measurement phase due to the limited availability of astronaut time), thereby limiting the completeness of subjective self-assessment data.

Preprocessing

We evaluated the acoustic (CPP) and EGG characteristics (jitter, f_0 , and contact quotient [CQ]) of sustained vowels as primary phonatory measures, along with MPT and pitch range. These measures were chosen for their established utility in characterizing glottal function and vocal fold vibratory behavior^{41,43}. The other tasks (singing, running speech, pitch matching task) are being analysed for a future publication.

For the sustained vowel recordings, the initial 500 ms were excluded, and the subsequent 3 s were used for analysis. This truncation minimizes transient phonatory initiation effects and optimizes the stability

of parameters for reliable assessment³². Further analysis was performed on the sustained vowel segments, focusing on f_0 , (in Hz), CQ, (in %), jitter (in %) and CPP, (in dB) with Voice Suite 11 (Laryngograph Ltd., London, UK).

MPT was calculated as the longest duration of sustained phonation on the vowel /o/. The minimum and maximum f_0 was manually extracted from the glissando recordings using Voice Suite, with the resulting pitch range converted to semitones.

From the standardized questionnaires, we used the total scores from the VTDS and VHI and the interest, joy, and anxiety subscales from the DES. These subscales were chosen because they capture emotional dimensions relevant to vocal performance and also exhibited variation across sessions.

Prior to statistical analysis, visually verified technical artifacts and physiologically implausible failures were excluded. Exclusions were minimal and did not alter the overall longitudinal patterns.

Statistical analysis

Statistical analyses were conducted in R (RStudio2025.09.2 Build 418, Posit team (2025). RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, MA. URL <http://www.posit.co/>). To evaluate phase-dependent changes in phonatory behaviour, segmented (interrupted) regression models were fitted separately for each outcome variable (CPP, jitter, CQ, f_0 , MPT, and pitch range). The general model included terms for baseline time, phase-related level changes (Phase B and Phase C relative to Phase A), and within-phase temporal trends. For phonatory variables, vowel was included as an additional fixed effect to account for vowel-specific differences. This modelling framework allowed differentiation between immediate shifts associated with phase transitions and gradual changes within phases.

Backup astronaut data were analysed to assess baseline stability. The phonatory measures were modelled as a function of time and vowel, while session-level measures (MPT and pitch range) were modelled as a function of time only. These analyses were used to evaluate potential temporal drift.

To complement model-based analyses, session-level descriptive statistics were computed for each phase, including mean values, percent changes relative to baseline, and standardized differences expressed in baseline standard deviation units. In addition, a non-overlap metric was calculated to estimate the proportion of observations in Phase B exceeding (or falling below) the range observed during Phase A, providing a distribution-based index of phase separation. To examine whether phonatory measures reflected coordinated changes in phonation principal component analysis (PCA) was conducted on standardized values of CPP, CQ, jitter, and f_0 . The first principal component (PC1) was analyzed using the same time-series framework.

Additional normative reference values were obtained from a separate healthy control dataset analysed independently from the matched longitudinal control recordings. This dataset included acoustically

healthy speakers and was used to establish reference distributions for CPP, jitter, CQ, f_0 , MPT, and pitch range. Descriptive statistics were calculated for each variable. Phase-specific descriptive statistics were calculated for the astronaut (Phases A, B, and C), while overall descriptive statistics were calculated for the matched backup astronaut. These values were then compared with the healthy control reference distributions.

For each variable, standardized deviation scores (z-scores) were calculated relative to the healthy control mean and standard deviation using the formula: where denotes the observed mean value of the target dataset, and μ_{HC} and σ_{HC} denote the healthy control mean and standard deviation, respectively. Variables were additionally categorized according to whether they remained within 1 SD, within 2 SD, or outside 2 SD of the healthy reference distribution. A binary indicator was also computed to determine whether observed values remained within the empirical healthy control range (minimum–maximum interval).

Questionnaire measures (VTDS, VHI, interest, joy, and anxiety) were analysed at the session level using the original raw scores. Descriptive statistics (mean, standard deviation, minimum, maximum) of questionnaire measures were calculated for each experimental phase (Phase A, Phase B, Phase C). Prior to statistical modeling, phonatory variables (CPP, jitter, CQ, and f_0) were aggregated to the session level by computing the per-session mean to ensure alignment of temporal resolution between subjective and phonatory measures.

To avoid multicollinearity among questionnaire variables, which showed substantial intercorrelations (e.g., VTDS–anxiety $\rho = 0.67$, joy–anxiety $\rho = -0.80$), each questionnaire predictor was entered into separate linear models. For each phonatory outcome, regression models of the following form were fitted:

$$\text{phonatory measure} \sim \text{session_num} + \text{Phase_B} + \text{Phase_C} + \text{time_B} + \text{time_C} + \text{questionnaire_z}$$

where questionnaire variables were standardized (z-scored) prior to analysis. This approach was chosen to ensure model identifiability given the limited sample size and high intercorrelation among predictors.

Model assumptions were evaluated for all regression analyses. Residual distributions were visually inspected using residual–fitted plots and Q–Q plots. Homoscedasticity and potential influential observations were assessed graphically. For interrupted time-series models, residual autocorrelation was inspected and considered during model interpretation. No severe violations requiring model reformulation were identified.

In addition to regression analyses, non-parametric Spearman correlations were computed between session-level questionnaire and phonatory variables to assess pairwise associations without model assumptions. This complementary approach was used to verify the robustness of observed relationships under conditions of limited sample size.

Given the limited number of repeated sessions and the exploratory nature of several analyses, interpretation focused primarily on consistency of patterns across complementary analytical approaches rather than isolated significance tests. Accordingly, descriptive phase comparisons, interrupted time-series modelling, changes expressed in baseline standard deviation units, non-overlap indices, PCA, and exploratory questionnaire analyses were considered jointly when evaluating the robustness of observed changes.

Results

Descriptive statistics

Table 1

summarizes the descriptive statistics of all vocal measures across healthy controls, the backup astronaut, and the three experimental phases of the astronaut (baseline-Phase A, inflight-Phase B, and postflight-Phase C).

Variable	Healthy controls	Backup Astronaut	Phase A	Phase B	Phase C
CPP	2.6 ± 0.9 (1.27–4.81)	1.71 ± 0.32 (1.13–2.39)	3.64 ± 0.86 (2.09–4.94)	2.65 ± 0.86(1.41–3.75)	3.59 ± 0.72 (2.25–4.52)
CQ	44.06 ± 5.82(32.8–59.32)	44.42 ± 2.56(39.39–50.47)	48.69 ± 2.96 (43.44–52.52)	45.16 ± 2.69 (39.9–50.56)	46.97 ± 2.32 (42.69–52.02)
f₀	102.99 ± 12.6 (79.85–128.15)	83.24 ± 5.68 (73.54–99.69)	118.97 ± 8.71 (103.08–131.19)	133.26 ± 7.72 (121.55–141.73)	127.25 ± 4.14 (121.05–135.02)
jitter	0.77 ± 0.3 (0.26–1.50)	0.79 ± 0.36 (0.44–2.3)	0.26 ± 0.06 (0.18–0.39)	0.40 ± 0.14 (0.23–0.83)	0.29 ± 0.08 (0.19–0.48)
MPT	26.22 ± 12.99 (14–69)	31.33 ± 5.87(23–40)	29 ± 1.24 (28–31)	35.33 ± 4.19 (30–40)	40.33 ± 1.27 (39–42)
Pitch Range	41.88 ± 11.6(23–58)	29.33 ± 3.64 (22–35)	25.75 ± 1.95 (24–29)	27.33 ± 3.84 (22–30)	30.33 ± 1.27 (29–32)

Table 1. **Comparative descriptive statistics (mean ± standard deviation, min, max) for vocal measures across healthy controls, backup astronaut, and the three experimental phases (Phase A= baseline, Phase B=inflight, Phase C= postflight) of the astronaut**

Visual inspection of the phase means suggested systematic shifts across several vocal domains during the inflight period. Compared with baseline (Phase A), the astronaut showed lower CPP and CQ values during inflight recordings (Phase B), accompanied by higher jitter and increased f₀. During the postflight period (Phase C), CPP moved closer to Phase A levels, jitter and CQ remained slightly elevated, whereas f₀ remained elevated relative to baseline.

To complement the descriptive statistics, phase-specific distributions of the primary phonatory outcomes of the astronaut are shown in Fig. 1. Violin plots with overlaid individual observations illustrate both central tendency and within-phase variability of CPP, CQ, f_0 , and jitter. Session-level trajectories of CPP, CQ, f_0 , jitter, MPT and pitch range of the astronaut and backup astronaut are shown on Fig. 2.

Time-series regression results

Interrupted time-series analyses revealed clear phase-dependent changes in several parameters. (Table 2.)

Table 2
Interrupted time-series regression estimates for longitudinal vocal measures

Variable	Parameter	β	SE	CI 95	p
CPP	time	0.066	0.013	0.041 to 0.091	< 0.0001
CPP	phase_B	-3.112	0.424	-3.958 to -2.266	< 0.0001
CPP	phase_C	-3.201	0.607	-4.412 to -1.991	< 0.0001
CPP	time_B	-0.058	0.023	-0.105 to -0.011	< 0.05
CPP	time_C	-0.042	0.033	-0.108 to 0.025	0.219
Jitter	time	-0.003	0.003	-0.01 to 0.003	0.31
Jitter	phase_B	0.229	0.109	0.013 to 0.446	< 0.05
Jitter	phase_C	0.179	0.162	-0.143 to 0.501	0.271
Jitter	time_B	0.005	0.005	-0.005 to 0.016	0.294
Jitter	time_C	0.008	0.009	-0.01 to 0.025	0.39
CQ	time	0.347	0.114	0.12 to 0.575	< 0.01
CQ	phase_B	-14.514	3.649	-21.779 to -7.248	< 0.001
CQ	phase_C	-17.552	5.433	-28.37 to -6.733	< 0.01
CQ	time_B	-0.25	0.175	-0.598 to 0.099	0.157
CQ	time_C	-0.499	0.299	-1.095 to 0.097	0.1
f0	time	0.032	0.327	-0.619 to 0.682	0.923
f0	phase_B	9.084	10.426	-11.676 to 29.843	0.386
f0	phase_C	1.437	15.523	-29.474 to 32.348	0.926
f0	time_B	0.711	0.499	-0.283 to 1.706	0.158
f0	time_C	1.984	0.856	0.28 to 3.687	< 0.05
MPT	time	0.079	0.042	-0.005 to 0.163	0.066
MPT	phase_B	8.785	1.338	6.124 to 11.446	< 0.0001
MPT	phase_C	5.7	2.01	1.702 to 9.698	< 0.01
MPT	time_B	-1.124	0.062	-1.247 to -1.001	< 0.0001
MPT	time_C	0.652	0.111	0.432 to 0.872	< 0.0001
Pitch Range	time	-0.409	0.085	-0.579 to -0.239	< 0.0001
Pitch Range	phase_B	11.091	2.699	5.724 to 16.458	< 0.0001

Variable	Parameter	β	SE	CI 95	p
Pitch Range	phase_C	22.057	4.055	13.994 to 30.12	< 0.0001
Pitch Range	time_B	1.066	0.125	0.818 to 1.314	< 0.0001
Pitch Range	time_C	1.024	0.223	0.58 to 1.469	< 0.0001

Table 2. Interrupted time-series regression estimates for longitudinal vocal measures (Cepstral Peak Prominence [CPP], Contact Quotient [CQ], fundamental frequency [f_0], jitter, Maximum Phonation Time [MPT, pitch range) across experimental phases. β coefficients, standard errors (SE), 95% confidence intervals (CI), and p-values are reported for baseline temporal trends (time), immediate phase-transition effects (phase_B, phase_C), and phase-specific slope changes (time_B, time_C). Positive β values indicate increases and negative values indicate decreases relative to the baseline trajectory.

CPP showed a marked decrease at the transition from Phase A to Phase B ($\beta = -3.11, p < 0.001$), accompanied by a further negative within-phase trend during Phase B ($\beta = -0.058, p = 0.016$). CPP remained significantly reduced in Phase C relative to baseline ($\beta = -3.20, p < 0.001$), with no additional within-phase trend in the return phase. Jitter exhibited a significant increase at the onset of Phase B ($\beta = 0.23, p = 0.038$), without evidence of systematic within-phase change. No significant level shift was observed in Phase C. CQ also showed a significant reduction in Phase B ($\beta = -14.51, p < 0.001$), which persisted in Phase C ($\beta = -17.55, p = 0.002$). In addition, a modest positive temporal trend was observed across the full time series ($\beta = 0.35, p = 0.003$), indicating baseline drift independent of phase transitions.

In contrast, f_0 showed a more complex temporal pattern. Descriptively, f_0 increased from Phase A to Phase B, with an initial rise at the onset of Phase B, followed by a transient decrease and a subsequent increase within the altered condition. However, interrupted time-series analyses did not indicate a statistically significant immediate level change at the transition to Phase B ($\beta = 9.08, p = 0.39$) or Phase C ($\beta = 1.44, p = 0.93$). Instead, a significant positive within-Phase trend was observed in Phase C ($\beta = 1.98, p = 0.023$).

Because sustained vowels were analysed jointly, vowel identity was included as a covariate in the interrupted time-series models for phonatory outcomes. Several outcomes showed significant vowel-specific differences in absolute values after adjustment for time and phase (CPP: lower values for vowel /u/, $\beta = -1.61, p < 0.001$; jitter: lower values for vowels /i/ and /u/, both $p < 0.001$; CQ: higher values for vowel /u/, $\beta = 2.06, p = 0.003$), indicating expected baseline differences across sustained vowels. Importantly, phase-related effects remained detectable after adjustment for vowel identity, suggesting that the observed temporal patterns cannot be explained solely by vowel-dependent acoustic variation.

Exploratory phase $\times$ vowel analyses suggested that phase-related temporal patterns were broadly comparable across vowels for jitter ($p = 0.171$) and f_0 ($p = 0.966$), with only trend-level evidence for CQ ($p = 0.066$). In contrast, CPP showed evidence of vowel-dependent modulation ($p = 0.039$), indicating that the magnitude of phase-related CPP changes differed across sustained vowels.

Session-level measures (MPT, pitch ranges) demonstrated patterns distinct from the primary phonatory variables. MPT increased significantly in Phase B ($\beta = 8.79, p < 0.001$) and remained elevated in Phase C ($\beta = 5.70, p = 0.006$). However, these changes were accompanied by strong within-phase temporal trends (e.g., $\beta = -1.12$ in Phase B, $p < 0.001$), suggesting progressive adaptation rather than a discrete phase-dependent effect. Similarly, pitch range increased across phases (Phase B: $\beta = 11.09, p < 0.001$; Phase C: $\beta = 22.06, p < 0.001$), with significant positive within-phase trends, indicating gradual changes over time rather than abrupt shifts.

In the case of backup astronaut, several parameters exhibited significant linear trends over time (Fig. 2.). Jitter increased ($\beta = 0.0078, p = 0.004$), while CQ also showed a gradual increase ($\beta = 0.076, p < 0.001$). In contrast, f_0 decreased over time ($\beta = -0.086, p = 0.005$), MPT showed a modest decline ($\beta = -0.070, p = 0.014$), whereas pitch range increased substantially ($\beta = 0.129, p < 0.001$). No significant temporal change was observed for CPP ($p = 0.55$).

Taken together, these findings indicate that several measures, particularly jitter, f_0 and pitch range, are susceptible to gradual time-dependent drift under stable conditions. These changes were generally monotonic and not accompanied by coordinated shifts across multiple parameters. The direction of change also differed between speakers, with f_0 decreasing in the control condition but showing a non-monotonic pattern in the case of the astronaut.

Non-overlap analysis results

Phase-level descriptive analyses supported the model-based findings (Table 3.).

Table 3
Descriptive phase-level changes, standardized effect sizes, non-overlap, and recovery indices across experimental phases.

Variable	A	B	C	$\Delta A \rightarrow B$ (%)	Effect size	AB non-overlap	Recovery
CPP	3.64	2.65	3.59	-27.21	-1.15	0.31	1
Jitter	0.26	0.4	0.29	51.85	2.22	0.41	0.89
CQ	48.69	45.16	46.97	-7.25	-1.19	0.18	0.93
f_0	118.96	133.26	127.25	12.02	1.64	0.68	0.78

Table 3. Descriptive phase-level changes, standardized effect sizes, non-overlap, and recovery indices across experimental phases. Mean values are shown for Phase A (baseline), Phase B (inflight), and Phase C (postflight). $\Delta A \rightarrow B$ (%) indicates the percentage change from baseline to inflight relative to the Phase A mean. Effect size represents the magnitude of the Phase A $\rightarrow$ B change expressed in baseline standard deviation units ($(B - A) / SD$ of Phase A), where larger absolute values indicate stronger deviation from baseline. AB non-overlap denotes the proportion of Phase B observations extending beyond the observed Phase A range in the expected direction of change and reflects the distinctness of

the altered condition relative to baseline. Recovery represents the proportion of Phase C observations returning within the observed Phase A range, with values approaching 1 indicating greater return toward baseline conditions. Negative values indicate decreases relative to baseline, whereas positive values indicate increases.

From Phase A to Phase B, CPP decreased by approximately 27% relative to baseline, while jitter increased by approximately 52%. These changes corresponded to standardized differences of -1.15 (CPP) and $+2.22$ (jitter) in baseline standard deviation units. CQ showed a smaller decrease (-7.3% , -1.19 SD), while f_0 increased moderately ($+12.0\%$, $+1.64$ SD). Non-overlap analyses indicated partial separation between phases, with 31% of Phase B observations for CPP and 41% for jitter falling outside the baseline range. The highest non-overlap was observed for f_0 (approximately 68%), although this was not supported by time-series evidence for an immediate phase-dependent shift. Recovery patterns differed across measures: CPP showed near-complete return to the baseline range in Phase C, whereas jitter, CQ and f_0 exhibited partial recovery.

Principal component analysis results

Principal component analysis (Fig. 3.) of CPP, CQ, jitter, and f_0 revealed a dominant first component reflecting shared variance among the primary phonatory measures.

CPP and CQ loaded positively, whereas jitter and f_0 loaded negatively on this component, indicating that it captured a dimension of phonatory stability. Time-series analysis of the first principal component confirmed a significant phase-dependent shift, consistent with coordinated changes in phonation. The relatively small loading of f_0 suggests that pitch were partly independent from the dominant covariance structure of voice quality measures.

Comparison with the healthy control reference distribution

Relative to the healthy control reference distribution, most phonatory and performance measures of the astronaut remained within the healthy range across phases. The only clear deviation was observed for f_0 during Phase B, which exceeded the healthy reference range and was more than two standard deviations above the healthy control mean ($z = 2.40$). In Phase C, f_0 decreased and returned within two standard deviations of the healthy reference distribution. Other parameters, including CPP, CQ, jitter, MPT, and pitch range, remained within the healthy reference range

Questionnaire measures and their relation to phonation

Questionnaire measures of the astronaut showed clear phase-dependent modulation. Vocal tract discomfort (VTDS) increased from Phase A (13.5 ± 5.45 , 9–21 [mean $\pm$ SD, min-max]) to Phase B (19.0 ± 7.07 , 14–24), followed by a marked decrease in Phase C (8.33 ± 1.15 , 7–9), falling below baseline levels. Interest increased substantially during Phase B (12.0 ± 0 , 12–12) compared to Phase A (8.25 ± 0.96 , 7–9) and returned to baseline levels in Phase C (8.0 ± 1.0 , 7–9). Joy showed a moderate increase from Phase

A (8.0 ± 1.83 , 6–10) to Phase B (10.5 ± 0.71 , 10–11) and further increased in Phase C (11.0 ± 0 , 11–11). In contrast, anxiety remained stable or slightly decreased across phases, from 28.0 ± 1.83 (26–30) in Phase A to 27.0 ± 0 (27–27) in Phase B and decreased further in Phase C (24.33 ± 0.58 , 24–25). Spearman correlation analyses revealed strong and consistent association between interest and multiple phonatory parameters. Higher interest was associated with lower CPP ($\rho = -0.85$, $p = 0.007$), lower CQ ($\rho = -0.85$, $p = 0.0037$), and higher jitter ($\rho = 0.88$, $p = 0.0015$). In contrast, self-reported interest was not significantly associated with any phonatory variable (all $p > 0.27$) after controlling for session-related temporal drift in the case of the backup astronaut.

No significant associations were observed between VTDS and phonatory measures (all $p > 0.4$). Similarly, anxiety did not correlate with any phonatory parameter (all $p > 0.4$). Joy showed moderate but non-significant associations with jitter ($\rho = 0.50$, $p = 0.17$) and CQ ($\rho = -0.52$, $p = 0.15$). Regression models including questionnaire predictors (entered separately) revealed a significant positive effect of interest on jitter ($\beta = 0.057$, $p = 0.0435$). No other questionnaire variables showed statistically significant effects on phonatory outcomes. Specifically, VTDS did not predict CPP ($\beta = -0.017$, $p = 0.957$), jitter ($\beta = -0.022$, $p = 0.449$), CQ ($\beta = 0.844$, $p = 0.719$), or f_0 ($\beta = 0.85$, $p = 0.931$). Joy was not associated with any phonatory parameter in regression models (all $p > 0.3$). Anxiety showed a significant positive association with f_0 ($\beta = 11.93$, $p = 0.0155$); however, this effect was not supported by correlation analysis and was therefore interpreted with caution.

VHI scores remained well below the pathological threshold throughout the study. Mean VHI values increased modestly from Phase A (9.0 , ± 2.15 , 6–12) to Phase B (12.5 , ± 1.54 , 11–14), followed by a marked reduction in Phase C (4.0 , ± 0.83 , 3–5) in the case of the astronaut. No sessions exceeded the predefined pathological threshold (30). The backup astronaut showed consistently minimal VHI scores (1.67 , ± 0.95 , 1–4), with no evidence of clinically relevant voice handicap.

Questionnaire measures showed structured intercorrelations. VTDS was positively associated with anxiety ($\rho = 0.67$, $p < 0.001$) and negatively associated with joy ($\rho = -0.58$, $p < 0.001$). In contrast, interest showed only weak correlations with other questionnaire variables ($|\rho| < 0.37$), suggesting that it represents a relatively independent dimension.

Discussion

The present study investigated microgravity-dependent changes in phonation using a single-case design combined with a matched control, and for reference range a matched, healthy control group (Table 4.).

Table 4
Summary of phase-dependent phonatory changes

Outcome	A→B change	Baseline-range non-overlap	ITS immediate level shift	B→C pattern	Healthy-control context	Matched-control drift
CPP	Strong decrease (- 27.2%)	Moderate (31%)	Significant ↓	Partial recovery	Within healthy range	Stable
jitter	Moderate increase (+ 51.8%)	Moderate (41%)	Significant ↑	Partial normalization	Within healthy range	Gradual increase
CQ	Moderate decrease (-7.3%)	Low–moderate (18%)	Significant ↓	Partial recovery	Within healthy range	Gradual increase
f ₀	Moderate increase (+ 12.0%)	High (68%)	No significant immediate shift	Non-linear / delayed adaptation	Phase B exceeded healthy range (> 2 SD)	Gradual decrease
MPT	Increase (+ 21.8%)	Minimal	Significant ↑	Continued increase	Within healthy range	Mild decrease
Pitch Range	Mild increase (+ 6.1%)	Low	Significant ↑	Continued increase	Within healthy range	Gradual increase

Table 4. Summary of phase-dependent phonatory changes Values represent phase-specific means for the baseline phase (A), in-flight phase (B), and post-flight phase (C). $\Delta A \rightarrow B$ (%) indicates the percentage change from Phase A to Phase B, calculated relative to the Phase A mean. Effect size is expressed as the change from Phase A to Phase B in baseline standard deviation units, calculated as (B mean – A mean) / SD, providing a standardized estimate of the magnitude of change. AB non-overlap represents the proportion of Phase B observations extending beyond the Phase A range in the expected direction of change (higher or lower depending on the variable), serving as a descriptive index of phase separation. Recovery indicates the proportion of Phase C observations falling within the observed Phase A range, reflecting the extent of return toward baseline values. (CPP, cepstral peak prominence; CQ, contact quotient; f₀, fundamental frequency)

The results revealed a consistent shift in phonation during microgravity, primarily reflected in decreased CPP, increased jitter, f₀ and reduced CQ. Together, these changes indicate a transition toward reduced phonatory stability.

Importantly, these effects were not restricted to isolated phonatory parameters but showed partial convergence across multiple dimensions of voice production. The strong interrelationships among CPP, jitter, and CQ, together with their shared contribution to the principal component analysis, suggest that these variables captured a common latent dimension related to phonatory control. In contrast, f_0 contributed less strongly to this shared structure, indicating that pitch-related changes may have been partly independent from the dominant covariance pattern.

Furthermore, phase-related effects remained detectable after adjustment for vowel identity. Exploratory phase $\times$ vowel analyses indicated that temporal response patterns were broadly preserved across vowels for jitter, CQ, and f_0 , whereas CPP showed evidence of vowel-dependent modulation. Together, these findings suggest a combination of broader phonatory adaptation.

f_0 exhibited a more complex temporal profile. Although descriptive analyses indicated an increase in f_0 during the altered condition, segmented regression modelling did not support a consistent immediate phase-related shift. Instead, f_0 showed a transient increase at the onset of Phase B, partial reduction, and subsequent increase within the phase. This dissociation suggests that pitch alteration may be secondary consequence of other changes in phonation. Previous research revealed that cognitive load is associated with increasing f_0 ⁴⁴. Moreover, the influence of stress on voice production parameters, including increased f_0 of speaking, has been documented in various psychosocial stress induction paradigms^{45,46}. The present data do not support a stress-related interpretation, as anxiety levels did not increase in microgravity. Rather, the observed f_0 changes may reflect adaptive adjustments in laryngeal control, under altered respiratory, somatosensory, and biomechanical conditions.

Across experimental phases, pitch range and maximum phonation time increased; however, MPT exhibited pronounced within-phase temporal trends. These patterns align with practice- or performance-induced adaptations rather than direct effects of the microgravitational environment. The decline in MPT during Phase B may indicate a fatigue-related effect.

Although some variability in phonatory measures was observed over time at the backup astronaut, these changes did not exhibit structured, phase-like patterns and were not coordinated across parameters.

The alterations in phonatory parameters under microgravity conditions likely reflect a perturbation-induced adaptive response of the vocal sensorimotor system, analogous to how the system compensates for auditory feedback discrepancies in terrestrial environments^{47,48} or proprioceptive deficits from body unloading⁴⁹ and postural adaptations impairing fine motor control in speech¹³. The observed decrease in CPP alongside increased jitter values provides evidence for enhanced vocal fold vibratory irregularity and reduced vocal stability, indicative of microgravity's influence on laryngeal control mechanisms^{50,51}. Proprioceptive feedback deficits due to body unloading in a reduced gravitational field could compromise precise laryngeal muscle coordination⁴⁹. These physiological alterations, particularly the increased jitter align with previous findings which indicate that microgravity

can significantly impair speech quality and vocal stability^{32,52}. Sound pressure level showed only minimal variation across phases, (89.1 dB in Phase A, 87.2 dB in Phase B, and 88.1 dB in Phase C) suggesting that the observed phonatory changes were unlikely to be attributable merely to altered vocal loudness.

The observed elevation in f_0 during microgravity exposure partially explains the concomitant decrease in CQ, as compensatory increases in subglottal pressure and laryngeal tension—primary drivers of elevated f_0 ^{52–54}—typically prolong the open phase of the glottal cycle, thereby reducing CQ in hyperfunctional phonation^{56,57}. However, the substantial increases in jitter suggest that microgravity also induces a level of vocal fold vibratory instability that cannot be solely attributed to increased tension.

One possible peripheral contributor to the observed phonatory changes during the spaceflight is the development of mild, transient vocal fold oedema. Increased vocal fold mass (like Reinke's oedema) is usually associated with reduced f_0 due to chronic mass loading^{57,58} and increased closed quotient^{58,59}. However, the present results showed the opposite pattern, with increased f_0 and reduced CQ during Phase B.

A decrease in CQ occurs when the vocal folds spend a smaller portion of each vibratory cycle in contact^{41,60,61}. Literature supports this finding in cases of both acute and chronic oedema. Acute inflammation or oedema can disrupt the vibratory characteristics and closure of the vocal folds⁶². This often prevents the folds from closing properly, leading to "incomplete glottal closure" and air leakage⁶². In cases of phonotraumatic vocal hyperfunction (which often involves oedema or lesions), patients exhibit elevated open quotient (OQ) values⁵⁶. Since CQ and OQ are inversely related, an elevated OQ indicates a significantly reduced CQ. The relationship between oedema and f_0 is complex. While standard clinical pathology often shows a decrease in f_0 , certain conditions and compensatory behaviors lead to an increase^{63–65}. Potential transient laryngeal oedema often require higher subglottal driving pressures to initiate and maintain vocal fold vibration⁵⁷ and increased subglottal pressure is a primary driver of elevated f_0 ⁵⁶.

This apparent discrepancy also suggests that oedema alone cannot account for the observed phonatory restructuring. Instead, the results are more consistent with a compensatory adjustment of laryngeal tension in response to subtle tissue-level changes. Increased longitudinal tension of the vocal folds may counteract mass-related lowering of f_0 resulting in elevated pitch despite possible swelling-related biomechanical alterations.

These findings suggest that transient oedematous changes may have contributed to altered vibratory behaviour but are unlikely to represent the primary driver of the observed phonatory shift. Instead, the combined pattern of increased f_0 , reduced CPP, reduced CQ, and increased jitter is more consistent with compensatory reorganization of phonatory control involving both peripheral biomechanical adjustments and central sensorimotor recalibration. Despite measurable phonatory changes during the altered condition, self-perceived voice handicap remained low across all phases. This dissociation suggests that

the observed phonatory alterations were largely subclinical and were not experienced as functionally impairing. The temporary increase in VHI during Phase B may reflect heightened vocal awareness or mild transient discomfort during the adaptation period. The score in the backup astronaut remained near floor level throughout the recording period.

Contrary to expectations, anxiety showed no consistent association with phonatory variables and did not increase during the altered condition. Similarly, VTDS did not reliably predict phonatory measures. Instead, the strongest and most consistent associations were observed for self-reported interest. In the backup astronaut, interest ratings showed no significant association with CPP, jitter, CQ, or f_0 after controlling for session-related temporal drift. So the present findings should be interpreted as evidence of covariation rather than direct causal influence between affective state and phonatory behavior. Further studies using larger longitudinal datasets and experimentally controlled affective manipulations would be required to clarify causal mechanisms.

Limitations and future plans

Due to the single-case study design the generalizability of these findings is limited. In addition, data loss due to technical issues and mission-related constraints further limits the generalizability of our findings. Nevertheless, given the limited access to and stringent constraints associated with microgravity research platforms, we believe that our results may still provide valuable insights for the field. Future longitudinal investigations with multiple participants—including pre-flight baselines, extended, targeted in-flight monitoring, and post-flight assessments—are warranted to establish causal mechanisms, quantify recovery trajectories, evaluate persistent effects following short-duration missions and examine the association between fluid shifts, vocal fold oedema, and vocal performance.

Conclusion

In conclusion, the present study delineates a complex interplay between microgravity and phonation, manifesting as significant alterations in f_0 , CPP, CQ and vocal jitter. These findings underscore the necessity for continued investigation into the underlying physiological mechanisms and the development of targeted countermeasures to maintain optimal vocal function during prolonged space missions. Specifically, future research should explore the correlation between these phonatory changes and individual physiological responses to microgravity, such as fluid shifts and sensorimotor adaptations, to elucidate the precise pathways through which spaceflight impacts vocal production^{39,47}. Moreover, a deeper understanding of these changes of vocal characteristics could help to monitor the health and performance of astronauts.

Declarations

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Author contributions

Conception and design: A.B., T.H., T.P., ZS.G., Analysis and interpretation: A.B., P.H., T.H., Data collection: Á.S., A.B., E.D.; Writing the article: A.B., T. H., Á. S., P.H., ZS.G.)

Data availability

Data supporting the findings of this study are available from the corresponding authors on reasonable request.

Competing interests

The authors declare no competing interests.

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Figures

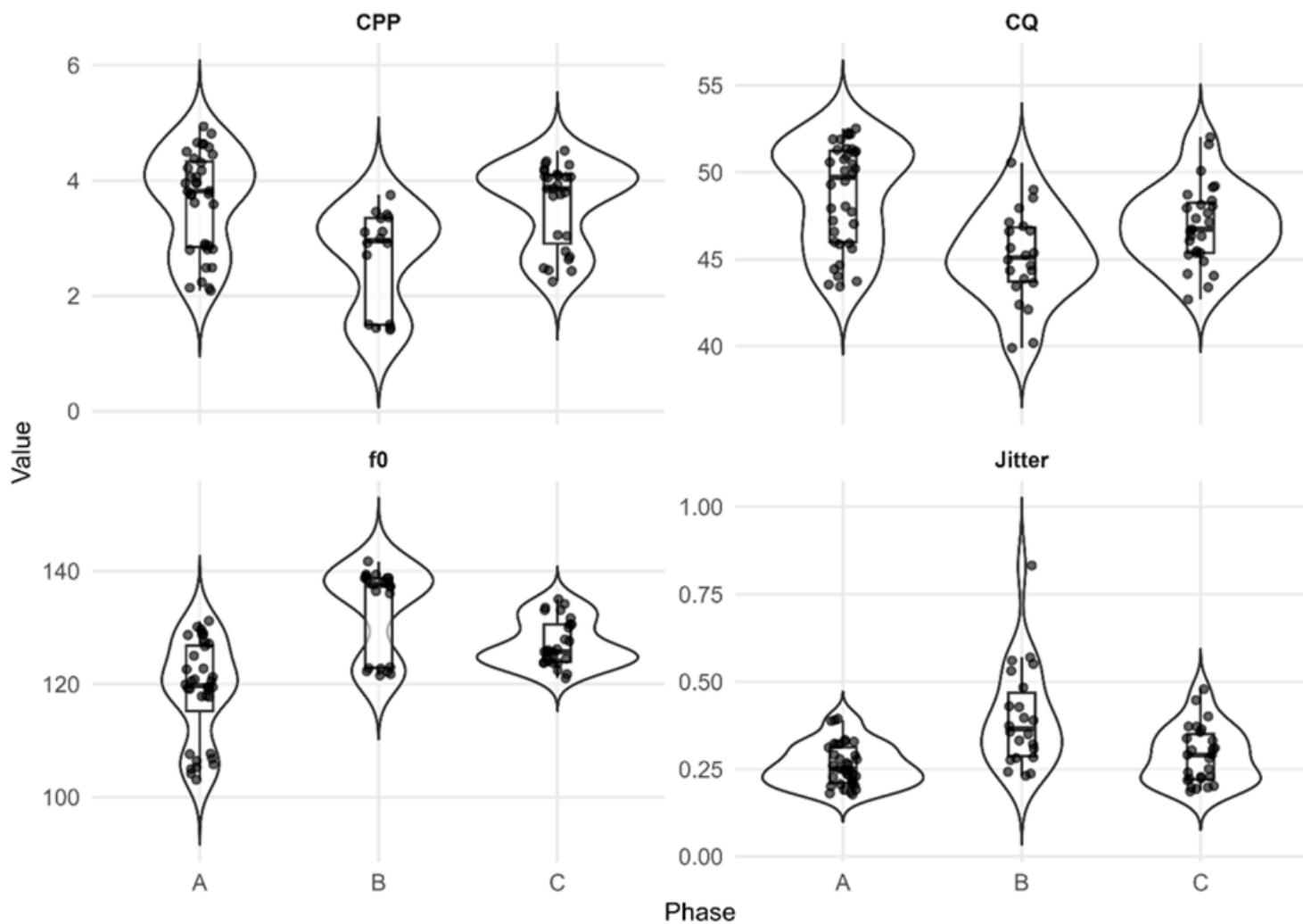


Figure 1

Distribution of vocal measures across the three experimental phases in the case of the flying astronaut. Violin plots show Cepstral Peak Prominence (CPP in dB), Contact Quotient (CQ in %), fundamental frequency (f0 in Hz), and jitter (in%) across Phases A (Baseline), B (Inflight), and C (Postflight), with overlaid points representing individual vowel-level observations.

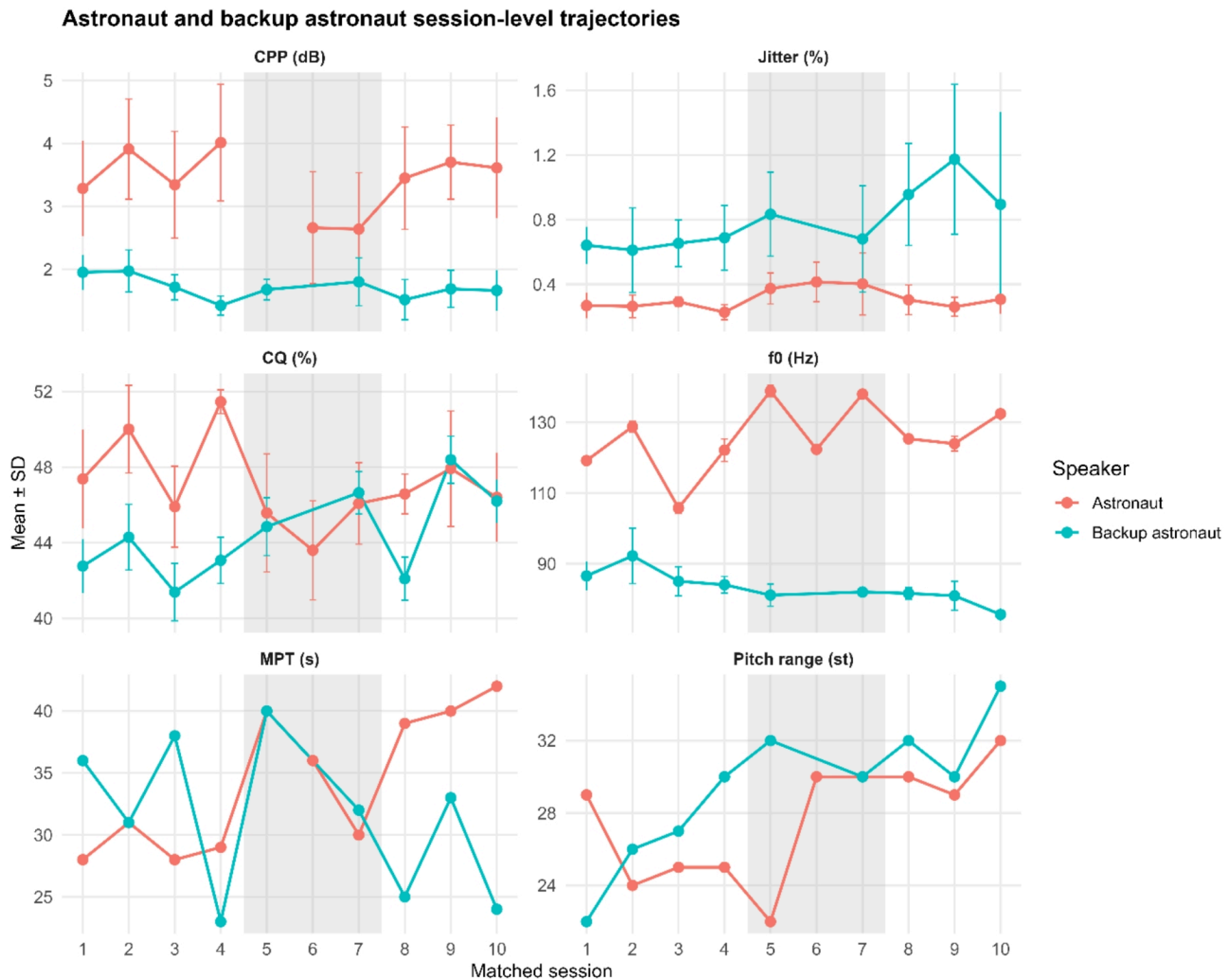


Figure 2

Longitudinal trajectories of vocal measures in the astronaut and backup astronaut. Session-level mean trajectories of Cepstral peak Prominence (CPP in dB), contact quotient (CQ in %), fundamental frequency (f_0 in Hz), jitter (in %), (with SD), maximum phonation time (MPT, in secundum [s]), and vocal range (in semitones [st]) for the astronaut and backup astronaut across matched recording sessions. The shaded region indicates the microgravity phase (Phase B).

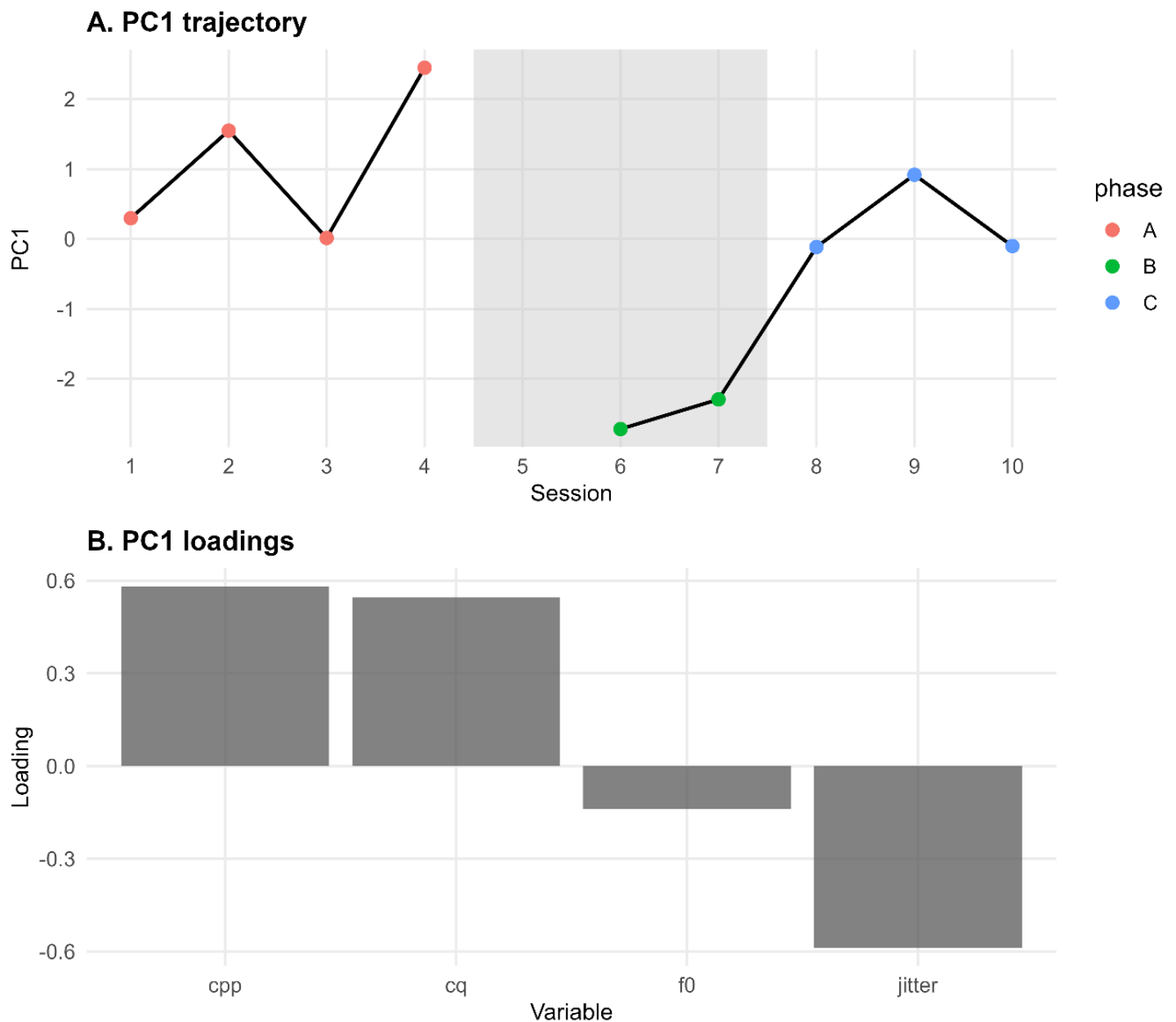


Figure 3

Longitudinal PC1 trajectory and variable loadings across experimental phases

(A) Session-level trajectory of the first principal component (PC1) derived from Cepstral peak Prominence (CPP), contact quotient (CQ), fundamental frequency (f_0) and jitter, across the three experimental phases. Higher PC1 values reflected increased CPP and CQ together with lower jitter and f_0 values, corresponding to greater phonatory stability. The shaded region indicates Phase B (inflight).

(B) Variable loadings contributing to PC1.