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Vomit Comet Physiology: Autonomic Changes in Novice Flyers

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***Abstract*— This exploratory study examined the effects of varying g-forces, including feelings of weightlessness, on an individual's physiology during parabolic flight. Specifically, we collected heart rate, accelerometer, and skin conductance measurements from 16 flyers aboard a parabolic flight using wearable, wireless sensors. The biosignals were then correlated to participant reports of nausea, anxiety, and excitement during periods of altered g-forces. Using linear mixed-effects models, we found that (1) heart rate was positively correlated to individuals' self-reported highest/lowest periods of both anxiety and excitement, and (2) bilateral skin conductance asymmetry was positively correlated to individuals' self-reported highest/lowest periods of nausea.**

I. Introduction

As space flight becomes more accessible to citizens without specialized training in freefall conditions or "weightlessness," the need for accessible, unobtrusive measures of well-being grows. A parabolic flight is often a precursor to space-based studies. During these flights, travelers experience 20-30 second periods of freefall, followed by a few seconds of "typical gravity" and then 10-15 seconds of "hypergravity" (sensations of >1 g-force), as the airplane flies in repeated aerial parabolas. The rapid variation of these g-forces (or rather, the departure of typical normal forces on a person's body), coupled with the vestibular experiences of floating and spinning during freefall, can sometimes induce strong sensations of nausea, earning parabolic flight planes the nickname, "vomit comets".

While veteran flyers such as astronauts and military pilots train for years in controlled environments to endure such g-force variation with ease, novice flyers are less prepared for what they might experience on these flights. Determining who may experience motion discomfort or nausea unobtrusively and then, ultimately, personalizing interventions for these flyers to reduce their symptoms, is significant to the success of the impending consumer space age.

For this study, we collected and analyzed more than four hours per person of multi-modal wearable sensor data, as well as self-reported measures of excitement, anxiety, and nausea from both veteran and novice flyers aboard a commercial parabolic flight. We hypothesized to see specific markers of heightened physiological arousal, including increases in heart rate, skin conductance (SC), and SC asymmetry between right and left wrists correlated to reports of nausea, anxiety, and excitement.

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In the following sections, we describe our data collection and analysis methods, followed by preliminary results from this study. Then, we discuss implications of these results, describe limitations of our study and of similar in-the-wild studies, and suggest future work before concluding.

II. Related Work

A. Motion sickness in space

Space motion sickness affects most space-flight crew members and includes symptoms such as drowsiness, cold sweating, nausea, and vomiting that arise as the brain and body acclimate to reduced g-forces [9]. Because astronauts typically experience the symptoms for the first few days of space travel, it is important that countermeasures are developed to optimize performance and wellbeing, especially when missions are short in duration (e.g., 7 days).

NASA and other researchers (e.g., [3], [8], [10], [12]) have investigated spatial orientation and motion sickness and found that symptoms of nausea were modulated by head movement and unfamiliar cues, such as lacking a referential "down" direction, especially during periods of hypergravity. However, most of the research to date has been conducted using only questionnaires or self-reports; this field is just beginning to use physiological sensors.

B. Physiology changes to anxiety, excitement, and nausea

It is well established that electrodermal activity (EDA; the changing electrical properties of the skin typically measured via skin conductance) can be used to study various affective states including anxiety (e.g., [4], [6], [17]). However, recent findings suggest that EDA be viewed not simply as a unitary measure of generalized arousal or stress, but also as an indicator of more specific affective information, depending on where and how it is measured. For example, Picard et al. showed that right-wrist SC levels increased more than those on the left wrist when a right-handed individual experienced social anxiety, threat, or "high-stakes situations of personal significance" [14]. Thus, the asymmetry between right and left SC levels may encode affective information that cannot be obtained from right or left levels alone.

Specific to motion sickness, Wan et al. found that phasic SC measured at the forehead correlated with self-reported motion sickness when induced by viewing an optokinetic rotating drum [18]. LaCount et al. found increases in both SC and heart rate in response to increased levels of nausea, induced by viewing horizontally translating stripes in an MRI scanner [11].

Heart rate (HR) and heart rate variability (HRV) have also been used to study periods of anxiety and excitement. Results typically indicate a positive correlation with HR and a negative correlation between HRV and excitement and anxiety (e.g., [2], [5]).

III. Methods

A. Data collection

Participants for the study were recruited from individuals who had already volunteered to fly aboard a chartered parabolic flight. The airplane was a modified Boeing 727-200F, whose interior had been emptied and padded, save for approximately 35 seats at the rear of the plane. For this particular parabolic flight, 31 individuals were aboard the plane: 6 individuals were employed by the parabolic flight company and had flown dozens of parabolic flights (hereafter, "veteran flyers") and 25 individuals had never experienced a parabolic flight (hereafter, "novice flyers"). The veteran flyers served as flight attendants and coaches throughout the flight. All participants, including "novice" flyers, had flown on multiple standard commercial airplane flights.

Note that this flight was chartered as a research flight: almost all of the novice flyers aboard were either conducting or supervising research projects during the flight. These projects ranged from virtual reality maze navigation in freefall to novel mechanisms for asteroid capture, and all involved unique experimental setups, as well as different cognitive and physical demands.

The study protocol was approved by the Massachusetts Institute Technology Institutional Review Board (# 1709084457). Participation was limited by the number of sensors available. After providing written informed consent, 16 individuals participated: 4 veteran flyers (3 female, 1 male; ages 32-65) and 12 novice flyers (7 female, 5 male; ages 25-61). All participants were right-handed.

All participants wore a wireless sensor on each wrist that measured SC, skin temperature, and 3-axis acceleration at a 4, 4, and 32 Hz sampling rate, respectively. Ten participants wore Embrace sensors (Empatica, Italy), and the remaining 6 participants wore E4 sensors (Empatica, Italy).[1] The E4 sensors also collected photoplethysmography (PPG) data at a 64Hz sampling rate, which were used for pulse rate calculations. These sensors were worn snugly, with dry electrodes on the inner wrist. In addition to their wrist sensors, 13 participants wore a Zephyr Biopatch sensor (Medtronic, USA) attached to their chests using sticky electrodes. These sensors collected 3-axis acceleration, heart rate (HR), skin temperature, and heart rate variability at a 1 Hz sampling rate.

Note that the Biopatch sensors calculate heart rates from the devices' raw ECG signals, while the E4 sensors derive pulse rates via peripheral (wrist) PPG measurements. While heart rate and pulse rate are fundamentally distinct, since all but a few of the participants were wearing Biopatch sensors and since pulse rate is generally a reasonable proxy for heart rate in real-world conditions (e.g., [7], [13]), we use the term "heart rate" throughout this paper to refer to cardiac measures from both sensors.

[1]Full disclosure: Picard is a co-founder and shareholder in Empatica.

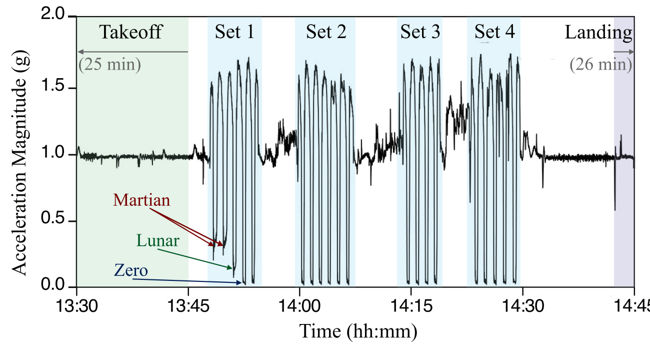

Fig. 1. Acceleration magnitude or "g-force" of the parabolic flight airplane, as measured by a commercially available accelerometer bolted to the floor of the plane [1]. Shaded regions denote the 6 flight segments used for analysis: takeoff, landing, and the four sets of parabolas. There were a total of 20 parabolas during the flight separated into sets of 4-6 parabolas each. Note that the first two parabolas simulated ∼20 second periods of Martian gravity (∼0.38 g), while the third parabola simulated lunar gravity (∼0.16 g). The fourth parabola was the first to simulate weightlessness or "zero gravity" (∼0 g).

All sensors were attached at least 1 hour prior to boarding the flight until approximately 30 minutes after deplaning. The timing was determined largely by the flight schedule and hangar access and was not adaptable for this study.

A three-axis accelerometer was bolted to the floor of the plane and recorded data throughout the flight [1]. These data were used as reference to determine different periods of altered acceleration or "g-forces." As the black line in Figure 1 depicts, there were a total of 20 parabolas during the flight split into 4 sets of 4-6 parabolas each. For this paper's analysis and the participant self reports, the flight was divided into 6 distinct periods: Takeoff (T), Landing (L), and the four sets of parabolic passes (hereafter, "Parabola Set 1, 2, 3, and 4," respectively). These regions are labeled and shaded in Fig. 1.

Before the flight, participants filled out a pre-flight questionnaire about their basic demographics (gender, age, parabolic flight experience). After returning to the hangar, participants filled out a post-flight questionnaire. In it, participants were asked to rank the 6 periods of the flight in order of decreasing excitement, anxiety, and nausea (independent of one another). For example, a participant might have experienced the greatest nausea during landing, followed by the parabola sets from last to first, with the least nausea during takeoff. (Nausea Rank for Participant X: L, 4, 3, 2, 1, T.) Alternatively, their excitement could have been greatest during the first parabola set, followed by takeoff, then parabola sets 2, 3, and 4, with the least excitement during landing. (Excitement Rank for Participant X: 1, T, 2, 3, 4, L.) Note that the "period" of the flight was used for these questions, instead of before or after each parabola, in order to decrease mental load, improve reliability, and reduce interference with participant research projects.

TABLE I

PHYSIOLOGICAL FEATURES CORRELATED TO SELF-REPORTED AFFECT FOR NOVICE FLYERS USING A LINEAR MIXED-EFFECTS MODEL

	$\overline{HR}$			$\overline{SC}_R$			$\overline{SC}_L$			$\overline{SC}_{R-L}$		
	β_1	p-value	N	β_1	p-value	N	β_1	p-value	N	β_1	p-value	N
Excitement	**2.6**	**<0.001**	**11**	1.31	0.152	8	0.60	0.077	11	0.49	0.259	8
Anxiety	**9.8**	**0.015**	**11**	1.06	0.061	8	0.58	0.112	11	0.35	0.331	8
Nausea	-1.2	0.124	9	0.36	0.178	7	0.00	0.979	9	**0.36**	**0.008**	**7**

B. Data processing and feature calculation

In order to ensure accurate timing synchronization, we first visually aligned the acceleration data from the plane with the acceleration data from the physiology sensors. In order to calculate the asymmetry between right and left wrist SC measurements, we used a linear interpolation to ensure that each time point had a concurrent left and right SC signal. For the 3 participants wearing E4 sensors without an additional Biopatch sensor, we linearly interpolated the PPG signals from both wrists to the same timestamps and took the average to improve the signal-to-noise ratio.

The mean SC, mean SC difference, and mean HR were then computed for each participant for the 6 distinct time periods: takeoff, parabola sets 1, 2, 3, and 4, and landing. The takeoff period was defined from the moment of liftoff to the 2 minutes before parabola set 1. It included ∼9 minutes of participants sitting while the plane reached altitude and ∼16 minutes of milling about the plane at constant altitude while participants prepped their research experiments. The timing for each parabola set included 1-2 seconds of level flight before that set's first parabola and 1-2 seconds of level flight after the set's last parabola; each set lasted approximately 6-8 minutes. Between each parabola set was a ∼5-minute period of level flight where participants were allowed to walk around the plane. After the last parabola, participants were allowed to move freely about the plane, secure their experiments, and return to their seats for landing. The landing period began ∼13 minutes after the end of the last parabola and lasted ∼26 minutes, until the plane touched down.

The mean SC signal for each wrist was computed for each period as follows: Let $SC_R(t)$ and $SC_L(t)$ be the right and left SC measurements, respectively, at time t, and let n_k be the total number of data points for the k^{th} flight period, where $k = [1, \cdots, 6]$. Then let $[t_{s_k}, t_{e_k}]$ be the period interval from start to end. Thus, the mean right SC for each period is defined as

$$\overline{SC}_{R_k} \equiv \frac{1}{n_k} \sum_{t=t_{s_k}}^{t_{e_k}} SC_R(t) \tag{1}$$

and likewise for $\overline{SC}_{L_k}$.

The mean difference between the right and left SC was computed for each flight period as follows:

$$\overline{SC}_{(R-L)_k} \equiv \overline{SC}_{R_k} - \overline{SC}_{L_k}. \tag{2}$$

Similarly, we computed the mean HR for each flight period: Let $HR(t)$ be the HR measurement at time t and n_k, k, and $[t_{s_k}, t_{e_k}]$ be defined as above. Then,

$$\overline{HR}_k \equiv \frac{1}{n_k} \sum_{t=t_{s_k}}^{t_{e_k}} HR(t). \tag{3}$$

C. Linear mixed-effects modeling

Implementing a consistent arousal-reducing baseline experience before the flight was not possible for this pilot study, nor were the landing or post-flight periods calm ones, as landing was accompanied by peak nausea for at least 4 participants. The immediate post-flight time was additionally stressful because flyers were required to remove their experiments and exit the hangar shortly after deplaning. Accordingly, in order to interpret the information from the biosignals, we needed to use an analysis method that was independent of a traditional baseline.

Hence, we used R [16] and nlme [15] to perform a linear mixed-effects (LME) analysis of the physiological signal *change* during participants' highest- vs. lowest-reported periods of nausea, anxiety, or excitement. Each affective state was assessed independently – e.g., highest nausea may have been during landing, while highest excitement may have been during parabola set 1. Lowest nausea may have been during takeoff, while lowest excitement may have been during landing.

We defined the LME model as follows: Let i be the i^{th} individual and j be the categorical variable for the lowest ($j \equiv 0$) and highest ($j \equiv 1$) ranked periods of reported affect. Then let $X_{i,j}$ be the physiological feature and $\epsilon_{i,j}$ be the residual. Then, the model with random intercept, β_{0i}, can be written as

$$X_{i,j} = \beta_{0i} + j\beta_1 + \epsilon_{i,j}. \tag{4}$$

This model allows us to test whether the physiological feature has increased (or decreased) during the period with the strongest reported emotion, corresponding to a positive (or a negative) slope, β_1, while partially accounting for individual differences via the unconstrained intercepts.

For this study, we evaluated the SC signal on the right hand, the left hand, the difference of these signals, and the HR for each affective feature. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. We calculated p-values using likelihood ratio tests, comparing the likelihoods of our mixed-effects models using a non-zero β_1 to the likelihoods for models with $\beta_1 = 0$ (our null hypothesis) for each case.

IV. Results & Discussion

A. Linear mixed-effects model

Table I summarizes the results of the LME model analysis for the mean HR, mean SC values from the right and left wrists, and SC mean difference (R-L). Bolded entries denote statistically significant results. The number of participants, N, varies between different correlation tests because (i) physiological measurements were missing due to sensor malfunction, (ii) self-reports were incomplete, or (iii) the participant did not experience that affect (e.g., 3 out of the 4 veteran coaches and 1 novice flyer reported experiencing no nausea at all; therefore there was no way to measure the *change* in their affect).

Using the LME model, we found a statistically significant increase in the SC mean difference (R-L) between the participants' self-reported period of lowest nausea compared to the period of highest nausea. We also found positive, statistically significant correlations between HR values and flyers' self-reported scores for both peak excitement and anxiety. The HR increase is greater (slope of 9.8) during periods of highest anxiety; however the finding is most statistically significant for highest excitement (slope of 2.6), which is consistent with other reports that HR is a meaningful and statistically significant measure of reported excitement [19].

As discussed in Section II-B, the Multiple Arousal Theory (MAT) posited by Picard et al. [14] suggests that right-wrist SC may increase more than left-wrist SC in response to anxiety, threat, or fear, especially when facing uncertainty in a personally significant high-stakes situation. Thus, we hypothesized greater activation of right SC over left during periods of higher reported anxiety and nausea. While our findings support the asymmetry predicted by the MAT for nausea, we failed to find a significant difference in asymmetry for anxiety. One possible explanation is that concomitant excitement during times of anxiety may boost the left SC, offsetting a relative R-L increase from the anxiety. A more controlled experimental setting is needed to securely decouple these competing states and their effects on differential SC.

B. Individual physiological profiles

The single-person SC (Figs. 2 and 4) and HR (Fig. 3) responses suggest that insight can also be gleaned from thick analyses of individual physiological signals. For example, the novice participant in Fig. 2 exhibits distinctive SC responses not only for each *set* of parabolas, but also for each individual parabola within each set. The rise of the phasic (fast-reacting) peaks in his SC corresponds with the moments immediately following the start of freefall. Note also that the highest global peaks of arousal occur not during the first three parabolas, which simulated Martian, Martian, and lunar gravity, respectively, but rather during the fourth and fifth parabolas, which were the first two experiences of "weightlessness." Similar timing and physiological responses are observed in the HR profile for a novice participant in Fig. 3.

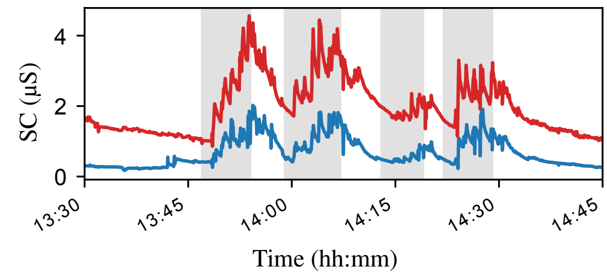

Fig. 2. Skin conductance for left (blue) and right (red) wrists during the parabolic flight for a novice participant. Gray areas denote the sets of parabolic passes. We note that this participant exhibited increased phasic SC during the sets of parabolic passes compared to level flight. We also observe asymmetry in the absolute increase of his right vs. left SC during periods of high arousal.

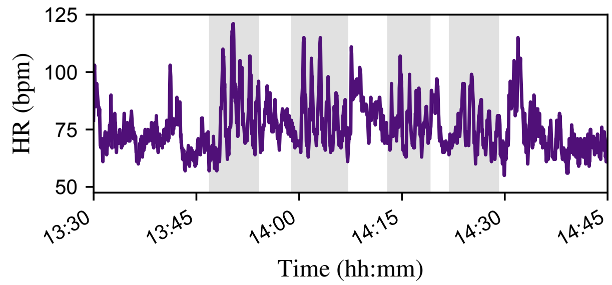

Fig. 3. Heart rate during parabolic flight for a novice participant, collected via a wireless chest-worn sensor with wet electrodes. Sets of parabolic passes are highlighted in gray.

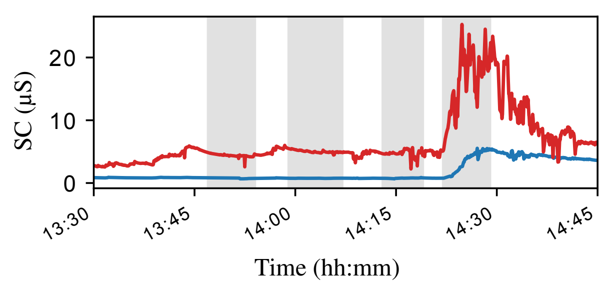

Fig. 4. Skin conductance for left (blue) and right (red) wrists during parabolic flight for a veteran participant. Sets of parabolic passes are highlighted in gray. During the final period of parabolic passes this participant had a large increase in SC on the right wrist.

In contrast, the SC responses from the veteran flyer shown in Fig. 4 indicate relatively steady SC during most of the flight, followed by a period of high arousal and strong SC asymmetry during the last set of parabolas.

While these results are promising, not all participants displayed such reactive physiological signals. For example, some individuals simply lack a strong SC signal in general, while others did not show strong responses to periods of altered g-forces.

C. Limitations

While analysis is ongoing, this exploratory study had a number of limitations. First, contrary to most laboratory studies, this study was conducted in the wild, with care taken to not interfere with the participants' personal research projects. This parameter limited the ability to repeatedly acquire reports of affective states from each participant during the flight – e.g., immediately after each period of parabolic passes, or even after each parabola – which induced an unavoidable degree of memory bias. Future studies will likely involve selecting participants who volunteer to report their affective states in real-time throughout the flight (using a body-worn cameras or audio recording devices, for example).

Second, participant stress or arousal may have been coupled not only to the novel parabolic flight experience, but also to their personal research experiments. Some individuals may have been relaxed or had success with their projects, while others may have been worried or encountered unexpected problems. Moreover, not all participants were doing active research; some were merely supervising passive experiments or were assisting others without a personal stake in their success. By asking each participant immediately after the flight about the moments of peak anxiety, we hoped to identify these personalized segments. While this exploratory study was only authorized as part of a research flight, future work includes running this study with novice flyers on *non*-research parabolic flights, as well as accounting for the types of participant activity – research or otherwise – in the analysis.

V. Conclusions

In conclusion, we collected physiological data from veteran and novice flyers ($N = 16$) aboard a commercial parabolic flight. Statistically significant differences were found in heart rate between participants' highest/lowest periods of both anxiety and excitement. Additionally, significant differences in bilateral skin conductance asymmetry (right-left differential) were hypothesized and found between flyers' highest/lowest periods of nausea. No significant differences were found using traditional single-hand skin conductance measurements for nausea, anxiety, or excitement. While these results are preliminary, they show the promise of wearable biosensors to provide valuable metrics of affect during space flight and other experiences of "weightlessness."

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