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High Heart Rate Variability Causes Better Adaptation to the Impact of Geomagnetic Storms

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Abstract: Our study aimed to test whether specific sensitive reactions in healthy males to the changes in geomagnetic activity (GMA) are different depending on the baseline self-regulation of the autonomic nervous system (ANS). In this study, the ANS response in the different phases of geomagnetic storms (GMSs) has been measured via the heart rate variability (HRV) using one-way ANOVA and the Bonferroni-adjusted *t*-test. In the case of high HRV, changes were found to indicate a significant intensification of both parts of the ANS: the sympathetic part (SP) showed increased stress levels and the parasympathetic part (PP) marked a self-regulation effort in the main and restoration phases of GMSs. In the case of low HRV, changes indicate a significant enhancement in the SP after the main phase of GMSs, with a day's delay. GMA is a sufficient environmental factor for healthy males, causing stress reactions of the ANS in the main and restoration phases of GMSs. However, the different self-regulation of the ANS results in different dynamics in its variation depending on the individual's character of the baseline ANS state; the optimal adaptation reactions of healthy males with baseline high HRV are achieved with decreased heart rate and increased HRV in the main phase of GMSs.

Keywords: adaptation stress reactions; autonomic self-regulation; geomagnetic storms; heart rate variability; the vagus nerve

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1. Introduction

In recent studies, disturbing variations of the geomagnetic field (GMF), such as geomagnetic storms (GMSs), are considered environmental stress factors, affecting human physiology, especially the cardiovascular, central, and autonomic nervous systems [1,2]. Some studies argued that the influence of meteorological factors such as the variation in daily averages of atmospheric pressure, relative humidity, and air temperature is less biologically effective than the influence of geomagnetic activity (GMA) [3]. The most common explanation of the human reactions is considered to be the triggering effect of sharp changes in the GMF during GMSs. Because the GMF strength varies during GMSs and increases hundreds of times depending on the latitude, it can play a role in human life-supporting systems or human health. During GMSs, existing diseases are aggravated; cases of myocardial infarction and death rise 25% and 5%, respectively; blood flow and coagulation time change; and blood pressure and cases of different kinds of arrhythmias increase [4–6].

In healthy people, effects can be manifested in the elongation of simple sensorimotor reaction time concerning the visual information processing speed, which indicates a decline in the attention parameters, especially short- and long-term memory. It is revealed that during the second day of a GMS, mistakes in proof tests are increased compared to the first GMS day, and 3–4 days after the GMS, the number of mistakes decreases [7]. This argues that during a GMS, humans are under the influence of the irritating (stress) effect. Studies have shown that heart rate sharply increases on days before, during, and after

GMSs [8]. During these days, heart rate variability (HRV) is also changed, and blood pressure and subjective psychophysiological complaints increase statistically significantly from day zero until the second day [9]. Changes in arterial pressure, pulse pressure, and participants' subjective psychophysiological status were revealed before, during, and 2 days after GMSs [10].

GMA is caused by solar activity. Solar periodical activity encompasses a cyclical pattern of solar magnetic pole reversals defining periodic changes in the sector structure of interplanetary magnetic fields. The solar non-periodical activity includes solar storms, solar energetic particle events, and coronal mass ejections (CMEs). CMEs and co-rotating interaction regions of solar wind (CIRs) can cause solar wind highspeed streams that can interact with the Earth's magnetosphere and consequently provoke disturbances. At the maximum of solar activity, GMSs are mainly caused by CMEs. CIRs mainly occur near the minimum of solar activity. Worldwide temporary disturbances of the GMF last over a period of several hours or days. GMSs can be characterized as having a sudden commencement, an initial phase, a main phase, and a phase of restoration [11,12]. GMA is maximal in the maximum or descending phases near the solar cycle maximum; in the minimum, it becomes minimal. Accordingly, the research results received in different solar phases are different.

The autonomic nervous system (ANS) response to GMF variations is measured via the HRV, mediated by the variation in the beat-to-beat interval of the heart [9,13,14]. Short-term rhythms in HRV are produced by the interactions between the autonomic neural activity, blood pressure, and respiratory control. HRV assesses the neurohumoral regulation of the heart and the relationship between the sympathetic and parasympathetic parts (SP and PP) of the ANS, and it is considered to be a measure of the neurocardiac function that reflects heart–brain interactions and ANS dynamics [15]. The main nerve of the parasympathetic nervous system is the vagus nerve; therefore, the parasympathetic activity is considered as vagal tone. The cardiac vagal tone as assessed by HRV measurement is also referred to as cardiac vagal control (CVC) [16].

According to the polyvagal theory, the vagus can rapidly regulate cardiac output to foster engagement and disengagement with the environment [17]. It is a complex of two directional systems that regulate homeostasis as well as associated responses to environmental challenges (i.e., stress); the adaptation function directly relates to the different levels of autonomic regulation in individuals [18]. In healthy adults, CVC is considered a physiological marker of emotion regulation; studies show that high baseline CVC is associated with better down-regulation of negative affect, the use of adaptive regulatory strategies, and more flexible emotional responses. Regarding phasic changes, decreased HRV/CVC indicates a stress response, while CVC increases have been shown to reflect either self-regulatory efforts or recovery from stress [19].

According to the standards of the European Cardiological Society and North American Society of Electrophysiology [20], the statistical characteristics of a dynamic number of cardio intervals include HR—Heart Rate, SDNN—Standard Deviation Normal to Normal R-R interval, RMSSD—the square root of the sum of squares of different values, and PNN50—the percentage of successive normal sinus RR intervals more than 50 ms. In short-term resting recordings, the primary source of the variation in SDNN is the parasympathetically mediated respiratory sinus arrhythmia (RSA). The RMSSD reflects the beat-to-beat variance in HR and is used to estimate the vagally mediated changes reflected in HRV; PNN50 is correlated with the RMSSD and HF power [21].

The spectral analysis of HRV records obtains quantitative data on oscillatory and wave processes in the cardio intervals, including high-frequency (HF—0.15–0.4 Hz), low-frequency (LF—0.04–0.15 Hz), very low-frequency (VLF—0.0033–0.04 Hz), and ultra-low-frequency (ULF—below 0.0033 Hz) bands. HF is related to the respiratory cycle mediating RSA and reflects parasympathetic or vagal activity. At resting conditions, both the SP and PP of the ANS are active with the vagal tone dominant [21]. SP inhibition reduces peripheral resistance, while PP activation depresses HR (reflex bradycardia) and contractility. In recent studies, several researchers [22,23] have argued that in the rest and short-term recordings, the LF band mainly reflects baroreflex and vagal activity and not cardiac sympathetic innervation [24]. Therefore, earlier suggestions that the LF band also reflects sympathetic activity and that the LF/HF ratio can be used as an assessment of the balance between sympathetic and parasympathetic activity [25] are currently controversial.

According to the Task Force, measuring the total power of frequencies and VLF from short-term recordings is physiologically ambiguous, and for this reason, their use is not recommended [20]. However, in the experimental works [26,27], the VLF rhythm is generated from the heart's intrinsic cardiac nervous system, and the amplitude and frequency of these oscillations are modulated by efferent sympathetic activity. Normal VLF power indicates healthy function, and their increase may reflect the increased sympathetic activity. The modulation of this rhythm during short-term recordings indicates that there is a significant stressor [28].

Reduced parasympathetic (vagal) activity has been found in many cardiac pathologies and patients under stress and anxiety. Low HRV has been confirmed as a strong predictor of future health problems and correlated to all causes of mortality because it reflects reduced regulatory capacity, which is the ability to adaptively respond to challenges like exercise or stressors [29–31].

According to the conceptual framework by Laborde et al. [32], CVC is reflected in four parameters of HRV: RMSSD, pNN50, the peak–valley analysis, and HF. In addition, there is another HRV indicator—RSA.

GMSs are also found to decrease HRV, indicating a possible mechanism of the GMF's influence on humans. This explains cardiovascular system aggravations as we described above because a reduced HRV is a prognostic factor for coronary artery diseases and myocardial infarction [5,33–35].

All above-mentioned studies investigated the effects of GMSs on humans, often including clinical populations without the inclusion of a healthy control group, and do not take into account the character of self-regulation of the investigated persons; only in a few studies have authors mentioned different physiological stress reactions on GMSs which are based on the ANS regulation type. These include studies performed on astronauts [2], on people living in the circumpolar region [36], and the studies performed on both healthy populations and people with cardiovascular diseases supporting the hypothesis that GMSs have different impacts on individuals, which is based on their sensitivity, health, and self-regulation type [13].

Based on this, the objective of our current study was to reveal the character of the induced reactions of healthy humans due to the changes in the different phases of GMSs, that can be different depending on the different baseline states of the ANS.

2. Materials and Methods

Our study was performed at a middle geomagnetic latitude (41°41′38″ N) in Tbilisi, Georgia, in 2022, corresponding to the ascending phase of the current solar cycle 25.

We examined n = 61 18 to 24 year-old healthy male medical students (volunteers). In order to receive a high reliability of the results, we only included the male group in the study, excluding females, taking into account specific physiological changes of females associated with the menstrual cycle which may alter HRV parameters during the study period [37].

Using the medium sample size for HRV studies [38], the group of participants was divided into two blocks (subgroups A and B), regarding their baseline autonomic states, into high and low HRV/CVC based on the above-mentioned variables: SDNN, RMSSD, pNN50, HF, and HR < 80 or HR > 80. Recordings were conducted in the light- and sound-shielded experimental room at the central scientific research laboratory (CSRL) of David Tvildiani Medical University (DTMU). Students were recorded on the days with different outdoor GMA, including days before and after GMSs and days with GMSs, which correspond to the initial, main, and restoration phases of GMSs. The study lasted for 3 months in spring. The detailed datasets used for analysis are available in the supplementary materials (Table S1).

The 1 h measurements of ANS responses to different GMA via comparison of the HRV indices with the Planetary K-index (index of magnitude of GMSs) were performed according to the appropriate methodical guidelines and recommendations [20,39], using the ArguSys++ Holter monitoring system by Innomed. hu.

The data on the current GMA for the middle latitude were obtained from the data of the Analysis Center for Geomagnetism and Space Magnetism Graduate School of Science, Kyoto University [40], for the classification of magnetically active days; days with $Kp \leq 3$ were ascribed as magnetically quiet, and those with $Kp \geq 5$ were ascribed as magnetically disturbed days [41].

Measurements were conducted after breakfast (at least by 1.5–2 h), with a constant temperature of 20–22 °C in the room, in a supine position with quiet breathing. A period of 10 min for the adaptation of volunteers to the local environmental conditions preceded measurements. In the 2 days before the recordings, a prerequisite precondition for the test volunteers was avoiding any negative influences resulting from emotional and physical excitation, heavy nutrition, alcohol, etc.

For statistical analysis of the data obtained, the "Primer of Biostatistics" software by Stanton A. Glantz (seventh edition) was used based on one-way analysis of variance—ANOVA—and multiple comparisons were conducted via the Bonferroni-adjusted t-test concerning the results of the homogeneity of variance. The significant level was taken as 0.05.

To check if our hypothesis was true, we summarized and computed the abovementioned HRV parameters; evaluated their means and standard deviations in the initial, main, and restoration phases of GMSs; and explained the differences between them.

3. Results

The variations in HRV indices in two subgroups in the cases of days before and after the main phase of GMSs (−1; + 1; $Kp \leq 3$) and those with GMSs (0; Kp = 5) are shown in Tables 1 and 2.

Table 1. Comparison of means and standard deviations of HRV parameters in subgroup A (high HRV/CVC) during different phases of GMSs.

Days	A	HR	SDNN	RMSSD	PNN50	VLF%	LF%	HF%
−1	13	75.5 ± 5.2	84.9 ± 17.4	58.4 ± 19.1	25.9 ± 9.4	30.4 ± 7.4	40.2 ± 9.6	29.2 ± 6.4
0	11	62.4 ± 8.7	94.9 ± 23	68.2 ± 20.1	34.9 ± 12.8	36.6 ± 8.4	34.02 ± 7.3	29.4 ± 8.1
1	9	70.4 ± 7.9	69.9 ± 12.9	52.1 ± 18.2	27 ± 14.7	26.7 ± 4.6	40.6 ± 5.1	32.6 ± 4.7
Between	SS	652.2	3110	1330	548.3	510.5	296.2	72.09
Between	DF	2	2	2	2	2	2	2
Between	MS	326.1	1555	665.1	274.2	255.2	148.1	36.05
Within	DF	30	30	30	30	30	30	30
	F	6.25	4.53	1.81	1.86	5.04	2.41	0.82
	P	0.005	0.019	0.181	0.173	0.013	0.107	0.452
t	I to II	4.781 *	4.244 *	1.62	2.559 *	2.910 *	2.641 *	0
t	II to III	3.486 *	1.862	2.626 *	1.814	3.978 *	2.407	1.419
t	I to III	0.903	2.463	1.021	0.269	1.374	0	1.471

Remarks: * indicates statistically significant differences; A—subgroup A; HR—heart rate, heart beats in min. (b/m); SDNN—Standard deviation of all Normal to Normal RR intervals in ms; RMSSD—the square root of the arithmetical mean of the sum of the squares of differences between adjacent NN intervals in ms; pNN50—the percentage of adjacent NN intervals that differ from each other by more than 50 ms; VLF—very low-frequency band; LF—low-frequency band; HF—high-frequency band; SS—sum of squares; DF—degrees of freedom; MS—mean squares; F—F value; P—*p* value.

Table 2. Comparison of means and standard deviations of HRV parameters in subgroup B (low HRV/CVC) during different phases of GMSs.

Days	B	HR	SDNN	RMSSD	PNN50	VLF%	LF%	HF%
−1	5	82.8 ± 1.6	54.4 ± 7.8	32.4 ± 16.1	10.8 ± 13.6	26.2 ± 7.6	45.7 ± 5.9	28.1 ± 7.1
0	11	86.5 ± 3.9	54.6 ± 8.6	30.7 ± 8.4	7.5 ± 5.1	28.1 ± 6.5	46.5 ± 7.5	25.5 ± 7
1	12	83.2 ± 2.6	45.8 ± 12.2	24 ± 7.6	4.3 ± 5.4	29.2 ± 11.3	46.1 ± 7.9	24.9 ± 5.9
Between	SS	75.08	532.7	370	159	31.31	2.182	38.1
Between	DF	2	2	2	2	2	2	2
Between	MS	37.54	266.4	185	79.48	15.66	1.091	19.05
Within	DF	25	25	25	25	25	25	25
	F	3.95	2.56	1.95	1.51	0.19	0.02	0.45
	P	0.032	0.098	0.163	0.241	0.828	0.981	0.645
t	I to II	2.551	0	0.269	1.084	0.289	0	0.803
t	II to III	3.296 *	2.655 *	2.087	1.4	0.374	0	0
t	I to III	0	2.082	2.182	2.196	0.586	0	1.22

Remark: B—subgroup B

As shown in Table 1, statistically significant differences between specific HRV indices are observed in subgroup A at the main and restoration phases of GMSs. A comparison of HRV indices between days −1, 0, and +1 clearly reveals the presence of sensitive reactions among those investigated. In the main phase of GMSs (0 days), there is a significantly reduced HR, which indicates the enhancement of the PP of the ANS, then HR significantly increased in the restoration phase of GMSs (+1 day), to return to baseline values.

PNN50 significantly increased in the main phase of GMSs, indicating the activation of the PP of the ANS. In the restoration phase of GMSs (+1 day), it decreased to the baseline values.

SDNN increased in the main phase of GMSs, indicating the presence of parasympathetically mediated respiratory sinus arrhythmia (see above), which is significantly canceled in the restoration phase of GMSs (+1 day). Interestingly, the value of SDNN in the restoration phase of GMSs (+1 day) is lower compared to the baseline values, and low values indicate a pronounced stress level and increased SP activities of the ANS because a higher SDNN is associated with a higher probability of survival [42].

The same trend is shown for RMSSD which increased in the main phase of GMSs, indicating the activation of the PP of the ANS. In the restoration phase of GMSs (+1 day), it decreased less compared to the baseline values. There was also significantly depressed LF in the main phase of GMSs, which returned to the baseline values in the restoration phase of GMSs (+1 day), also indicating the activation of the PP of the ANS.

VLF significantly increased in the main phase of GMSs, and then it significantly decreased in the restoration phase of GMSs (+1 day); as we described above (see Section 1), the modulation of this rhythm during short-term recordings indicates a significant stressor [27].

This means that GMSs are a significant environmental stress factor causing all the above-mentioned changes in healthy males' ANS during the main phase of GMSs, which are canceled by the self-regulation effort during the restoration phase of GMSs.

As presented in Table 2, differences between certain indices were observed in subgroup B compared to the baseline values. HR increased during the main phase of GMSs but it was not statistically significant and then returned statistically significantly to the baseline values during the restoration phase of GMSs.

SDNN was the same as the baseline value in the main phase of GMSs and then reduced statistically significantly in the restoration phase of GMSs (+1 day), indicating increased stress level and SP activities of the ANS.

The same trends show that RMSSD, PNN50, and HF reduced in the main and restoration phases of GMSs, indicating decreased PP and increased SP activities of the ANS.

We interpreted some HRV indices that are related to the CVC. We did not interpret the LF/HF ratio due to its physiologically controversial meaning as we described above.

Based on the analysis of the data received, it was determined that many indices of HRV that are related to the vagus nerve are sensitive to changes in different phases of GMSs; these include the HR and time domain (SDNN and PNN50) components of HRV. In addition, we found that the heart's intrinsic VLF rhythm, which is related to the efferent sympathetic activity, was changed significantly in the different phases of GMSs, indicating the presence of the pronounced environmental stress factor.

Figures 1 and 2 show significant changes in HRV parameters indicating cardiac vagal tone (HR, SDNN, RMSSD, and PNN50) and sympathetic activity (VLF) during different phases of GMSs in the case of initial high/low HRV, respectively.

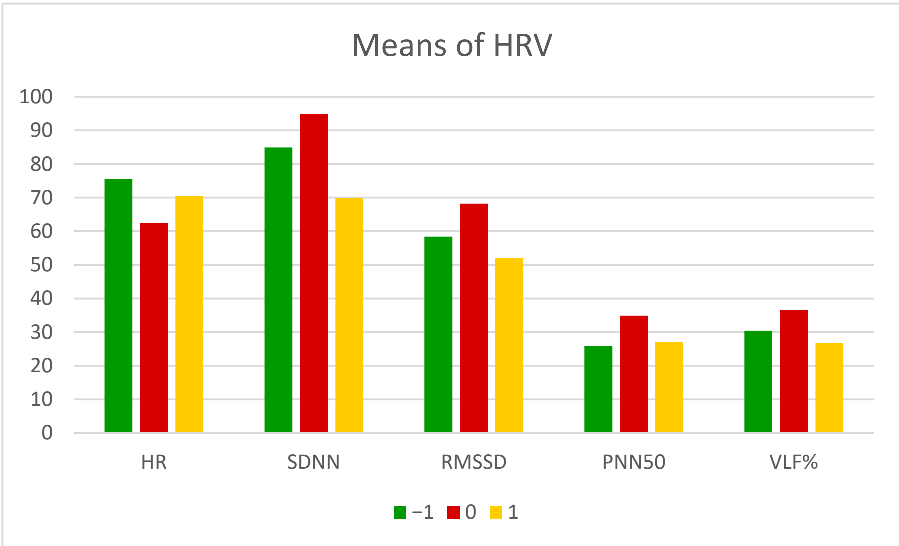

Figure 1. Changes in cardiac vagal tone and sympathetic activity during different phases of GMSs in the case of initial high HRV.

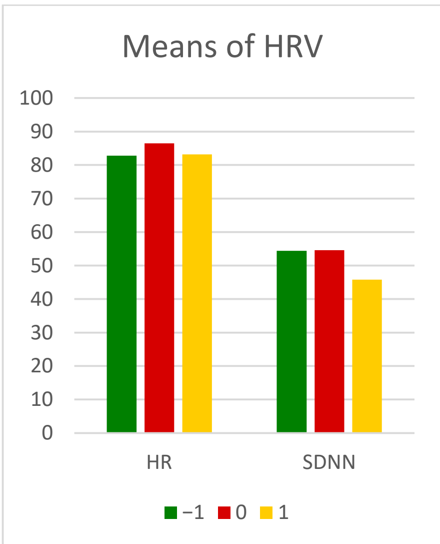

Figure 2. Changes in cardiac vagal tone during different phases of GMSs in the case of initial low HRV.

4. Discussion

As shown by the results of our study, in the case of high HRV/CVC (subgroup A), changes were found to indicate a significant intensification in PP on the GMS days, as an immediate self-regulatory effort. This is associated with down-regulation of the negative effect of GMSs manifested in the substantial intensification in the SP (VLF rhythm), using adaptive regulatory strategies [19].

In the case of low HRV/CVC (subgroup B), changes indicate increased stress levels and a significant intensification of SP on days after GMSs; the delay is one day.

It seems that the volunteers with a baseline high HRV/CVC compared with the low HRV/CVC are more adaptable to the impact of different phases of GMSs. The adaptation reactions are manifested in decreased HR and increased HRV. This fact could be explained by the high regulatory capacity and the better ability to adapt to environmental changes in volunteers having a higher baseline HRV/CVC.

The results of our study confirm the polyvagal theory of Porges [17,18], concerning the mechanisms of regulation of the heart rhythm, namely that the organism's autonomic nervous system supports adaptive responses to safety. The vagus nerve inhibits the influence of the SP on heart activity and reduces the stress response to the environment. The SP of the ANS, together with the endocrine system, responds to threats to our safety through the mobilization of an adaptive system. The SP responds more slowly and for a longer period than the vagus system.

The given results coincided with the neurovisceral integration model by Thayer et al. [43], which considers heart rate variability as the central autonomic network, providing the output from the brain structures. This network remotely regulates the interplay of sympathetic and parasympathetic influences on the heart and is associated with self-regulation processes. By this model, in cases of threat or stress, the sympathoexcitatory circuits activate the organism to respond to the threatening event.

Results are found that confirm the concept by Bernston et al. [44], that the PP and SP competitively regulate HR (accentuated antagonism), where increased sympathetic activity is paired with decreased parasympathetic activity and that both branches of the ANS are simultaneously active.

The findings of this study confirm the concept that vagally mediated HRV has been linked to optimal psychophysiological well-being in normal people, because HRV is increased at rest or when experiencing relaxation in a safe environment; conversely, in the case of stress, HRV is decreased, with a following increase in sympathetic activation (reflecting the activation of the defensive system). A reduced HRV in response to an environment marks stress, while an increased HRV underlies the positive states [19,33,35,42,45].

Our outcomes partly confirm earlier results from Dimitrova et al. [9], for the periods of minimal solar activity where HR increased during and after the storms, with significantly varied HRV parameters on these days.

Furthermore, the obtained results strengthen results received by Dimitrova [10], for the periods of maximal solar activity, which reveal an increase in significant average values of systolic, diastolic blood pressure, pulse pressure, and subjective complaints of the examined compared with geomagnetic activity increment.

Based on the given results, we confirm the findings of previous studies by [36,46], who determined that the character of resting self-autonomic regulation of local inhabitants living in subarctic areas caused different reactions to the impact of GMSs and the graded response of HRV is associated with an alteration of geomagnetic activity.

By comparing our findings with other research, our results coincide with the results of Breus et al. [2], who revealed that the initial autonomic regulation state in astronauts together with the duration of the flight causes a character of adaptation.

The received results confirm those found by Alabdulgader et al. [13], who examined long-term relationships between changes in solar and magnetic activity and ANS responses, revealing different manners of people's reactivity depending on an individual's autonomic state and capacity for self-regulation.

The current study has some limitations due to the inability of continuous monitoring of research subjects, in the university lab conditions, taking into account medical students' hard learning courses/routine/practice.

5. Conclusions

The performed study consistently showed that increased GMA such as GMSs produce real health effects. Interpretations of the received results are summarized here:

- GMSs are a sufficient environmental stress factor for healthy males' ANS in the ascending phase of the solar cycle.
- ANS response to the exposure to GMSs showed an intensification of both parts of the ANS, though baseline types of ANS self-regulation resulted in different dynamics of alterations during different phases of GMSs.
- The volunteers with high resting HRV/CVC compared with low HRV are more adaptable to the impact of different phases of GMSs, and the adaptation reaction is manifested in a decreased heart rate and increased HRV.

These conclusions give support for the hypothesis that the character of the induced reactions of healthy humans to the changes of different phases of GMSs is different depending on the different self-regulation of the ANS. This issue is closely related to the problem of developing criteria for assessing the level of an individual's response to geomagnetic disturbances.

The methodology used in this study will allow for the prediction of sensitive reactions in both healthy and ill persons during different phases of GMSs. Therefore, taking into account autonomic self-regulation types in healthy humans will play a role in choosing those individuals whose work environment is connected to stress and raised risks during GMSs (pilots, astronauts, drivers, air traffic controllers, high voltage line operators, etc.). This way, the effectiveness of their work and a reduction in errors will be achieved.

Furthermore, the methodology could be used in magneto-sensitive patients for the correction of drug-therapy regimens to facilitate the restoration of the balance between the sympathetic and parasympathetic parts of the ANS.

We propose to continue such studies by collecting and analyzing more data. Indeed, a coordinated multi-nation analysis study to search systematically for correlations with variations in solar-induced geomagnetic activity and human autonomic self-regulation would provide more data that would either support or refute the current results.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14121707/s1, Table S1: HRV recordings of healthy males during the study period (spring, 2022).

Author Contributions: A.R., writing—original draft, investigation, data acquisition, formal analysis, visualization; K.J., writing—original draft, conceptualization, methodology, investigation, validation; L.T., data curation, methodology, project administration, resources, supervision. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: In this work, the following ethical standards were complied with: the laws of Georgia, the Helsinki Declaration, as well as data protection stipulations. The study was approved by the Ethics Committee of DTMU (protocol code 03/2021, 29 April 2021).

Informed Consent Statement: Informed written consent was obtained from all subjects involved in the study.

Data Availability Statement: The detailed datasets with the exact dates of the geomagnetic storms used for analysis during the current study are available in the supplementary materials.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cherry, N. Schumann Resonances, a plausible biophysical mechanism for the human health effects of Solar/Geomagnetic Activity. *Nat. Hazards* **2002**, *26*, 279–331. [CrossRef]
2. Breus, T.; Baevsky, R.; Chernikova, A. Effects of geomagnetic disturbances on humans functional state in space flight. *J. Biomed. Sci. Eng.* **2012**, *5*, 341–355. [CrossRef]
3. Dimitrova, S. Investigations of some human physiological parameters in relation to geomagnetic variations of solar origin and meteorological factors. In Proceedings of the 2nd International Conference on Recent Advances in Space Technologies, RAST 2005, Istanbul, Turkey, 9–11 June 2005; pp. 728–733. [CrossRef]
4. Vencloviene, V.; Babarskien, R.; Kaminskaite, B.; Vasiliauskas, D. The Effect of Solar-Geomagnetic Activity During Hospital Admission on the Prognosis of Cardiovascular Outcomes in Patients with Myocardial Infarction. *Br. J. Med. Med. Res.* **2013**, *3*, 1587–1597. [CrossRef]
5. Cornelissen, G.; Halberg, F.; Breus, T.; Syitkina, E.; Baevsky, R.; Weydahl, A.; Watanabe, Y.; Otsuka, K.; Siegelova, J.; Fiser, B.; et al. Non-photic solar assotiations of heart rate variability and myocardial infarction. *J. Atmos. Sol.-Terr. Phys.* **2002**, *64*, 707–720. [CrossRef]
6. Stoupel, E. Sudden cardiac deaths and ventricular extrasystoles on days of four levels of geomagnetic activity. *J. Basic Physiol. Pharmacol.* **1993**, *4*, 357–366. [CrossRef]
7. Khorseva, N. Using psychophysiological indices to estimate the effect of cosmophysical factors. *Izv. Atmos. Ocean. Phys.* **2013**, *49*, 839–852. [CrossRef]
8. Mavromichalaki, H.; Papailiou, M.; Dimitrova, S.; Babayev, E.; Loucas, P. Space weather hazards and their impact on human cardio-health state parameters on Earth. *Nat. Hazards* **2012**, *64*, 1447–1459. [CrossRef]
9. Dimitrova, S.; Angelov, I.; Petrova, E. Solar and geomagnetic activity effects on heart rate variability. *Nat. Hazards* **2013**, *69*, 25–37. [CrossRef]
10. Dimitrova, S. Different geomagnetic indices as an indicator for geo-effective solar storms and human physiological state. *J. Atmos. Sol.-Terr. Phys.* **2008**, *70*, 420–427. [CrossRef]
11. Borovsky, J.E.; Denton, M.H. Differences between CME-driven storms and CIR-driven storms. *J. Geophys. Res.* **2006**, *111*, A07S08. [CrossRef]
12. Verbanac, G.; Vršnak, B.; Veronig, A.; Temmer, M. Equatorial coronal holes, solar wind high-speed streams, and their geoeffectiveness. *Astron. Astrophys.* **2011**, *526*, A20. [CrossRef]
13. Alabdulgader, A.; McCraty, R.; Atkinson, M.; Dobyns, Y.; Vainoras, A.; Ragulskis, M.; Stolc, V. Long-Term Study of Heart Rate Variability Responses to Changes in the Solar and Geomagnetic Environment. *Sci. Rep.* **2018**, *8*, 2663. [CrossRef]
14. McCraty, R.; Atkinson, M.; Stolc, V.; Alabdulgader, A.; Vainoras, A.; Ragulskis, M. Synchronization of Human Autonomic Nervous System Rhythms with Geomagnetic Activity in Human Subjects. *Int. J. Environ. Res. Public Health* **2017**, *14*, 770. [CrossRef]
15. McCraty, R.; Atkinson, M.; Tomasino, D.; Bradley, R.T. *The Coherent Heart: Heart-Brain Interactions, Psychophysiological Coherence, and the Emergence of System-Wide Order*; Integral Review; Institute of HeartMath, HeartMath Research Center: Boulder Creek, CA, USA, 2006; pp. 12–20.
16. Laborde, S.; Mosley, E.; Thayer, J.F. Heart Rate Variability and Cardiac Vagal Tone in Psychophysiological Research. *Front. Psychol.* **2012**, *20*, 213. [CrossRef]
17. Porges, S.W. The polyvagal theory: Phylogenetic substrates of a social nervous. *Int. J. Psychophysiol.* **2001**, *42*, 123–146. [CrossRef]
18. Porges, S.W. *The Polyvagal Theory: Neurophysiological Foundations of Emotions, Attachment, Communication, and Self-Regulation*, 1st ed.; W.W. Norton & Company: New York, NY, USA, 2011.
19. Balzarotti, S.; Biassoni, F.; Colombo, B.; Ciceri, M. Cardiac vagal control as a marker of emotion regulation in healthy adults: A review. *Biol. Psychol.* **2017**, *130*, 54–66. [CrossRef]
20. European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart Rate Variability Guidlines. *Eur. Heart J.* **1996**, *17*, 354–381. Available online: https://www.escardio.org/static-file/Escardio/Guidelines/Scientific-Statements/guidelines-Heart-Rate-Variability-FT-1996.pdf (accessed on 1 March 1996).
21. Shaffer, F.; McCraty, R.; Zerr, C.L. A healthy heart is not a metronome: An integrative review of the heart's anatomy and heart rate variability. *Front. Psychol.* **2014**, *5*, 1040. [CrossRef]
22. Rahman, F.; Pechnik, S.; Gross, D.; Sewell, L.; Goldstein, D.S. Low frequency power of heart rate variability reflects baroreflex function, not cardiac sympathetic innervation. *Clin. Auton. Res.* **2011**, *21*, 133–141. [CrossRef]
23. Heathers, J.A. Sympathovagal balance from heart rate variability: An obituary. *Exp. Physiol.* **2012**, *97*, 556. [CrossRef]
24. De Lartique, G. Putative roles of neuropeptides in vagal afferent signaling. *Physiol. Behav.* **2014**, *136*, 145–150. [CrossRef]
25. Pagani, M.; Lombardi, F.; Guzzetti, S.; Rimoldi, O.; Furlan, R.A.; Pizzinelli, P.; Sandrone, G.; Malfatto, G.; Dell'Orto, S.; Piccaluga, E. Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interactions in man and conscious dog. *Circ. Res.* **1986**, *59*, 178–193. [CrossRef]
26. Kember, G.; Fenton, G.; Collier, K.; Armour, J. Aperiodic stochastic resonance in a hysteretic population of cardiac neurons. *Phys. Rev. E* **2000**, *61*, 1816–1824. [CrossRef]
27. Armour, J.A. Potential clinical relevance of the "little brain" on the mammalian heart. *Exp. Physiol.* **2008**, *93*, 165–176. [CrossRef]
28. Bernardi, L.; Valle, F.; Coco, M.; Calciati, A.; Sleight, P. Physical activity influences heart rate variability and very-low-frequency components in Holter electrocardiograms. *Cardiovasc. Res.* **1996**, *32*, 234–237. [CrossRef]

29. Tsuji, H.; Larson, M.G.; Venditti, F.J.; Manders, E.S.; Evans, J.C.; Feldman, C.L.; Levy, D. Impact of reduced heart rate variability on risk for cardiac events: The Framingham Heart Study. *Circulation* **1996**, *94*, 2850–2855. [CrossRef]
30. Giardino, N.D.; Chan, L.; Borson, S. Combined heart rate variability and pulse oximetry biofeedback for chronic obstructive pulmonary disease: A feasibility study. *Appl. Psychophysiol. Biofeedback* **2004**, *29*, 121–133. [CrossRef]
31. Dekker, J.M.; Schouten, E.G.; Klootwijk, P.; Pool, J.; Swenne, C.A.; Kromhout, D. Heart rate variability fromshort electrocardiographic recordings predicts mortality from all causes in middle-aged and elderly men. The Zutphen Study. *Am. J. Epidemiol.* **1997**, *145*, 899–908. [CrossRef]
32. Laborde, S.; Mosley, E.; Mertgen, A. A unifying conceptual framework of factors associated to cardiac vagal control. *Heliyon* **2018**, *4*, e01002. [CrossRef]
33. Otsuka, K.; Cornélissen, G.; Weydahl, A.; Holmeslet, B.; Hansen, T.L.; Shinagawa, M.; Kubo, Y.; Nishimura, Y.; Omori, K.; Yano, S.; et al. Geomagnetic disturbance associated with decrease in heart rate variability in a subarctic area. *Biomed. Pharmacother.* **2001**, *55* (Suppl. 1), 51s–56s. [CrossRef]
34. Otsuka, K.; Yamanaka, T.; Cornelissen, G.; Breus, T.; Chibisov, S.M.; Baevsky, R.; Halberg, F.; Siegelova, J.; Fiser, B. Altered chronome of heart rate variability during span of high magnetic activity. *Scr. Med.* **2000**, *2*, 111–116.
35. Gmitrov, J.; Ohkubo, C. Geomagnetic field decreases cardiovascular variability. *Electromagn. Magnetobiol.* **1999**, *18*, 291–303. [CrossRef]
36. Chernouss, S.; Vinogradov, A.; Vlassova, E. Geophysical hazard for human health in the Circumpolar Auroral Belt: Evidence of a relationship between heart rate variation and electromagnetic disturbances. *Nat. Hazards* **2001**, *23*, 121–135. [CrossRef]
37. Beery, A.K.; Zucker, I. Sex bias in neuroscience and biomedical research. Neurosci. *Biobehav. Rev.* **2011**, *35*, 565–572. [CrossRef]
38. Quintana, D.S. Statistical considerations for reporting and planning heart rate variability case-control studies. *Psychophysiology* **2017**, *54*, 344–349. [CrossRef]
39. Nunan, D.; Sandercock, G.R.; Brodie, D.A. A quantitative systematic review of normal values for short-term heart rate variability in healthy adults. *Pacing Clin. Electrophysiol.* **2010**, *33*, 407–1417. [CrossRef]
40. Geomagnetic Data Service. Available online: https://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html (accessed on 5 September 2023).
41. Menvielle, M.; Iyemori, T.; Marchaudon, A.; Nose, M. Geomagnetic indices, K index limits. In *Geomagnetic Observations and Models*, 2011th ed.; Mandea, M., Korte, M., Eds.; Springer: Dordrecht, The Netherlands, 2011; p. 201.
42. Kleiger, R.E.; Miller, J.P.; Bigger, J.T.; Moss, A.J. Decreased heart rate variability and its association with increased mortality after acute myocardial infarction. *Am. J. Cardiol.* **1987**, *59*, 256–262. [CrossRef]
43. Thayer, J.F.; Yamamoto, S.S.; Brosschot, J.F. The relationship of autonomic imbalance, heart rate variability and cardiovascular disease risk factors. *Int. J. Cardiol.* **2010**, *141*, 122–131. [CrossRef]
44. Berntson, G.G.; Thomas Bigger, J., Jr.; Eckberg, D.L.; Grossman, P.; Kaufmann, P.G.; Malik, M.; Nagaraja, H.N.; Porges, S.W.; Saul, J.P.; Stone, P.H.; et al. Heart rate variability: Origins, methods and interpretive caveats. *Psychophysiology* **1997**, *34*, 623–648. [CrossRef]
45. Groves, D.; Brown, V. Vagal nerve stimulation: Are view of its applications and potential mechanisms that mediate its clinical effects. *Neurosci. Biobehav. Rev.* **2005**, *29*, 493–500. [CrossRef]
46. Oinuma, S.; Kubo, Y.; Otsuka, K.; Yamanaka, T.; Murakami, S.; Matsuoka, O.; Ohkawa, S.; Cornelissen, G.; Weydahl, A.; Holmeslet, B.; et al. Graded response of heart rate variability, associated with an alteration of geomagnetic activity in a subarctic area. *Biomed. Pharmacother.* **2002**, *56* (Suppl. 2), 284s–288s. [CrossRef]