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ORIGINAL ARTICLE

Exploring the relationship between geomagnetic activity and human heart rate variability

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Abstract

Purpose Both geomagnetic and solar activity fluctuate over time and have been proposed to affect human physiology. Heart rate variability (HRV) has substantial health implications regarding the ability to adapt to stressors and has been shown to be altered in many cardiovascular and neurological disorders. Intriguingly, previous work found significant, strong correlations between HRV and geomagnetic/solar activity. The purpose of this study to replicate these findings. We simultaneously measured HRV during a 30-day period.

Methods We recruited 20 healthy participants and measured their HRV for a 30-day period. We also collected geomagnetic and solar activity during this period for investigating their relationship with the HRV data.

Results In agreement with previous work, we found several significant correlations between short-term HRV and geophysical time-series. However, after correction for autocorrelation, which is inherent in time-series, the only significant results were an increase in very low frequency during higher local geomagnetic activity and a geomagnetic anticipatory decrease in heart rate a day before the higher global geomagnetic activity. Both correlations were very low. The loss of most significant effects after this correction suggests that previous findings may be a result of autocorrelation. A further note of caution is required since our and the previous studies in the field do not correct for multiple comparisons given the exploratory analysis strategy.

Conclusion We thus conclude that the effects of geomagnetic and solar activity are (if present) most likely of very small effect size and we question the validity of the previous studies given the methodological concerns we have uncovered with our work.

Keywords Heart rate variability · Geomagnetic activity · Solar activity

Abbreviations

HF	High-frequency power
HRV	Heart rate variability
LF	Low-frequency power
RMC	Repeated measures correlation
VLF	Very low-frequency power

Introduction

Heart rate variability (HRV), an analysis of the change in the time intervals of consecutive heartbeats, is a well-established physiological measurement that serves as an indicator

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of disease and mortality risk (Shaffer et al. 2014). Previous studies have suggested that a higher degree of HRV is indicative of better health and lower risk for disease. For example, low HRV has been linked to myocardial infarction (Buccelletti et al. 2009), neuropathy (Sztajzel 2004), depression (Blood et al. 2015), and schizophrenia (Yang et al. 2010). Diverse factors can modulate HRV, including genetic, neurological, respiratory, cardiovascular, lifestyle, and environmental factors (Malik and Camm 1990). Analysis of HRV in the frequency domain is also used to estimate the activity of both the sympathetic and parasympathetic nervous system, though it has also been found to be dependent on heart rate and other confounding factors and thus possibly not necessarily a valid measure of autonomic activity (Monfredi et al. 2014).

Recent studies found that the change in the magnetic field of the earth caused by solar activity is significantly correlated with HRV (McCraty et al. 2017; Alabdulgader et al. 2018). These studies were motivated by the relationship between cardiovascular health, specifically the occurrence of myocardial infarction, and both solar and geomagnetic activity (Baevsky et al. 1997; Chernouss et al. 2001). Yet, the relationship between HRV and geomagnetic activity remains unclear since several studies found conflicting results (Watanabe et al. 2001; Dimitrova et al. 2013). Here, we attempted to replicate a previous study that showed strong and significant correlations between HRV and solar geomagnetic activity in a small pilot study (McCraty et al. 2017; Alabdulgader et al. 2018). We found significant correlations between solar/geomagnetic activity and short-term HRV components before correction for the autocorrelation inherent to time-series. However, we only found an increase in very low-frequency HRV component and an anticipatory effect in heart rate with geomagnetic activity after correction for autocorrelation. Both effects were small; thus, previous studies have likely overestimated the effects due to the lack of stringent statistical analysis.

Methods

Participants

We enrolled a total of 20 healthy participants over the age of 18 into this 30-day longitudinal observational study. We recruited participants from the University of North Carolina at Chapel Hill area (Chapel Hill, NC, USA). Exclusion criteria included neurological or cardiovascular conditions, medication associated with these conditions, as well as pregnancy and daily meditation, which have been shown to affect HRV (Klinkenberg et al. 2009; Krygier et al. 2013). This study was approved by the Biomedical Institutional Review Board of the University of North Carolina at Chapel Hill. All participants provided written informed consent before participating in the study. All methods were performed in accordance with the relevant guidelines and regulations.

Materials

Each participant was provided with a commercially-available Firstbeat Bodyguard 2 (Firstbeat Technologies Oy, Jyväskylä, Finland) heart rate monitor and electrodes as well as the accompanying Firstbeat Uploader software (https://www.firstbeat.com). The monitor is worn on the torso with one electrode attached to the skin below the right collarbone, and the other electrode attached to the left ribcage; we instructed participants to move the electrode each day in a rotation of a few different spots to minimize skin irritation. The device automatically starts recording once both electrodes are attached, stores data internally, and has a battery life of approximately six days. Data were uploaded by participants through the Firstbeat software and REDCap (www.project-redcap.org), a secure online data collection portal for clinical research (Harris et al. 2009).

Procedure

After recruitment, participants first uploaded a short sample recording to ensure that they were able to follow the study procedure. Once all these "practice samples" were obtained, participants were told the dates of the 30-day data collection period, which was from October 24th, 2017 to November 22nd, 2017. Participants were instructed to begin wearing the monitor the night before the first day of the recording period. Participants were asked to wear the heart rate monitor nearly 24 h/day and to only take it off for showering or other events that could cause water or other damage to the device. Participants uploaded data every 4 days; this pace allowed for participants to charge their device before the battery drained and for the research team to properly monitor data upload progress. If participants failed to consistently upload data, they were contacted by a member of the research team to provide data for the missing days. To upload their data, participants first loaded their data onto their computer through the Firstbeat uploader program and subsequently used a queue of surveys from REDCap for upload. In each survey, participants indicated the date(s) of the recording(s) and any time periods that they did not wear the monitor. They were also reminded to charge the monitor.

Data collection concluded after 30 days. At this time, we contacted participants to ensure that they had uploaded all collected data and to schedule a time to collect the device and provide compensation. To encourage participants to wear the monitor as often as possible, compensation included a flat $50 payment as well as a maximum bonus payment of $200 per participant. The amount of bonus a participant received was based on the amount of data provided, with compensation exponentially increasing with the amount of data provided.

Environmental measurements

The K (Boulder) and Ap indices were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Information (https://www.ncei.noaa.gov) and are reported in 3-h intervals. The K index was obtained from Kyoto University's Data Analysis Center for Geomagnetism and Space Magnetism (https://wdc.kugi.kyoto-u.ac.jp/index.html). The F10.7 index was obtained from NASA's Omniweb Data Explorer (https://omniweb.gsfc.nasa.gov) and is reported in 1-h intervals.

Data analysis

For 12 of the 20 participants analyzed, there were various clearly incorrect timestamps, which occurred when the devices reset to their factory restoration timestamp in 2015 for an unknown reason. If possible, these times were corrected based on several identifiers, including relation to adjacent files, file upload timestamps, comparison between gaps in data and participant-identified times of not wearing the monitor, as well as other clues. Only files for which the correct time was determinable with high confidence were included (allowable margin of error: 15 min). Timestamps that could not be confidently corrected were not included in analysis. Eight participants had no errors in timestamps, nine participants had incorrect timestamps limited to the first five days or less, two participants had nearly half their data with incorrect timestamps, and one participant was not included in data analysis due to early withdrawal (reason: skin irritation). All-time points for each participant were then concatenated into a single series and corrected to account for gaps in the time series created when participants did not wear the monitor. These times were finally adjusted to match UTC time to compare them to the environmental data.

RR interval data were first processed in Kubios HRV Premium, ver. 3.0.2 (Tarvainen et al. 2014). The automatic artefact correction method in Kubios was used to correct for ectopic, too long, or too short beats by interpolating new RR values. Missed beats were corrected by adding new R-wave occurrence times and extra beats were corrected by removing extra R-wave detection and recalculating RR interval series. Further manual inspection of the RR series indicated that few artefacts were not removed and we thus removed RR values above 2.5 s or below 0.2 s.

Time and frequency domain analyses were completed in MATLAB R2016b (Mathworks, Natick, MA). Recordings were first split into 5-min intervals as comparison of HRV between recordings of different lengths is not meaningful (Malik and Camm 1990). Analysis was only completed for intervals containing data for at least 270 of the 300 s, and these results were then averaged into either 1-h or 3-h segments for comparison to environmental data. The criterion of at least 270 s of data per interval was based on a previous study that indicated this length as the minimum duration for correct estimation of the signal components studied here (Baek et al. 2015). For time-domain analysis, mean heart rate (HR), the standard deviation of RR intervals (SDNN), HRV triangular index (HRVTi), and the square root of the mean squared differences of successive RR intervals (RMSSD) indices were calculated. Standard deviation of average RR intervals (SDANN) results was not included, as this index is very similar to SDNN with 5-min recordings. For frequency analysis, very low-frequency power (VLF; 0.0033–0.04 Hz), low-frequency power (LF; 0.04–0.15 Hz), high-frequency power (HF; 0.15–0.4 Hz), LF/HF ratio (LF/HF), and total power (VLF + LF + HF) were obtained (Ori et al. 1992; Montano et al. 2009). Subsequently, a 24-h moving average was used to remove circadian rhythms from HRV components.

We performed the Repeated measures correlation (RMC) analysis, a form of ANCOVA (Bakdash and Marusich 2017). RMC produces a common within-subject correlation effect between two variables. Overall, this method produces a single correlational value indicating how two variables are correlated. RMC was also used to correlate time-series of HRV components between participants. This allowed the HRV of participants to be compared to each other without a dependence on time, testing the synchronization of HRV over the duration of the measurement period.

Correction for autocorrelation

When two time-series are being correlated with each other, the obtained results are possibly artificially inflated since individual samples of time-series are not independent due to inherent autocorrelation. To account for this, we used surrogate data by shuffling the HRV data (Small and Tse 2003; Nakamura and Small 2005; Louis et al. 2010). The HRV data were shuffled in time-domain while keeping the original environmental data structure in place. We ran the same correlation analyses in this new dataset (Fig. 1 as an example of shuffling). As a tradeoff exists between destroying the correlation of the two time-series and preserving the autocorrelation within the HRV data, we chose the window size for the shuffling such that there were at least 50 to ensure that the surrogate signals were sufficiently scrambled. Thus, the HRV data with time points of 3-h were shuffled in groups of 5 time points, and data with time points of 1-h were shuffled in groups of 12 time points. This approach creates shuffled time-series that still exhibit most of the autocorrelation

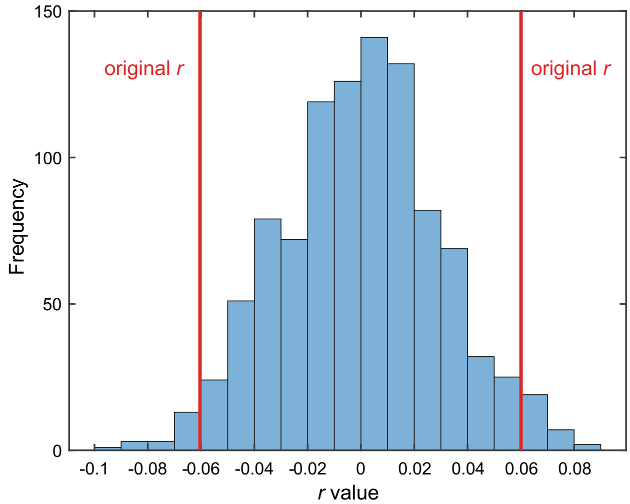

Fig. 1 Histogram of shuffled RMC values for VLF_{ratio}. The two red vertical lines indicate the original RMC value r and $(-1)*r$, which demonstrate the two-tailed test as the p-value was calculated by counting the instances where the absolute value of the original RMC value was greater than the absolute value of the shuffled RMC value

between neighboring samples but lack the temporal relationship with the other time-series it is correlated with. For each correlation, data were shuffled 1000 times, producing 1000 new RMC values. Empirical p values that have accounted for autocorrelation were then obtained with the equation:

$$p = \frac{n\_tail + 1}{n + 1}$$

where, p probability that obtained RMC values are greater than shuffled RMC values, n_tail amount of shuffled RMC absolute values that are greater than the original RMC absolute values, n amount of shuffles (1000 in this study).

Note that we adopted this equation instead of $p = r/n$ to avoid $p = 0$ when $n\_tail = 0$.

This two-tailed test was used to calculate the p-value for every statistic presented. We report both raw and shuffle-corrected p-values since previous studies did not perform this correction for autocorrelation.

Results

Data recorded

Of the 20 participants, three dropped out before completing data collection due to self-reported excessive skin irritation caused by the electrodes. Two of the three withdrawn participants ceased participation after the halfway point, so their data were included in the analysis; data from the third dropout was not included, leaving the study with 19 datasets. An average of 84.04% of the total 720 h (30 days × 24 h) were reported for the 19 participants. The maximum data provided was 702 h and the minimum amount of data included in the analysis was 321 h. Per participant, there was an average of 123 h of time-corrected data included in analysis or an average of 261 h for the nine participants with corrected data. The largest obstacle to obtaining more data was the skin irritation caused by continuous use of the electrodes. An example of raw data time-series in heart rates is presented (Fig. 2).

Correlations of HRV components

All HRV components were significantly correlated (Table 1, $p < 0.001$, both with and without the correction for autocorrelation). Measurements of overall variability were all positively correlated with each other and negatively correlated with heart rate. Each frequency-band percentage was inversely correlated to the others, an obvious relationship due to the shared denominator in their calculation. Total power was positively related to each measure of overall variability and HF_{ratio} (%), and negatively related to LF_{ratio} (%) and VLF_{ratio} (%), indicating that the HF band was responsible for the increase in the total power spectrum.

Geomagnetic and solar activity

Ap index is a linear scale indicating global geomagnetic activity; values below 7 indicate a quiet period, values from 7 to 48 indicate an active or unsettled period, values from 48 to 80 indicate a minor storm, and values from 80 to 130 indicate a major storm. There were three notable geomagnetic events during the data collection period (Fig. 3). The period 10/24–10/27 and 11/20–11/22 had small peaks in disturbance levels, peaking at 39 and 48, respectively, indicating periods of unsettled to a borderline minor storm of geomagnetic activity. A much larger event is noticeable in the 11/06–11/09 period, with a peak of 94 on 11/08, indicating that a major geomagnetic storm occurred. We also used the K index (Boulder magnetometer), which represents a semi-logarithmic 0–9 scale indicating local geomagnetic activity with 9 being the most activity. K_p index is an average of all global K indices, proving a semi-logarithmic measure of global activity. Values of each index varied from 0–6 during the time period of data collection, with the maximum of 6 occurring on 11/08 (Fig. 4), the same day as the A_p index maximum value. Unsurprisingly, the A_p index was strongly correlated to both the K index ($r = 0.77$, $p < 0.001$) and the K_p index ($r = 0.86$, $p < 0.001$); the K and K_p indices were also strongly correlated to each other ($r = 0.85$, $p < 0.001$).

For solar activity, F10.7 index is presented, which exhibited the lowest value around 11/8 (Fig. 3). F10.7 index stands for solar radio flux at a wavelength of 10.7 cm and is a direct

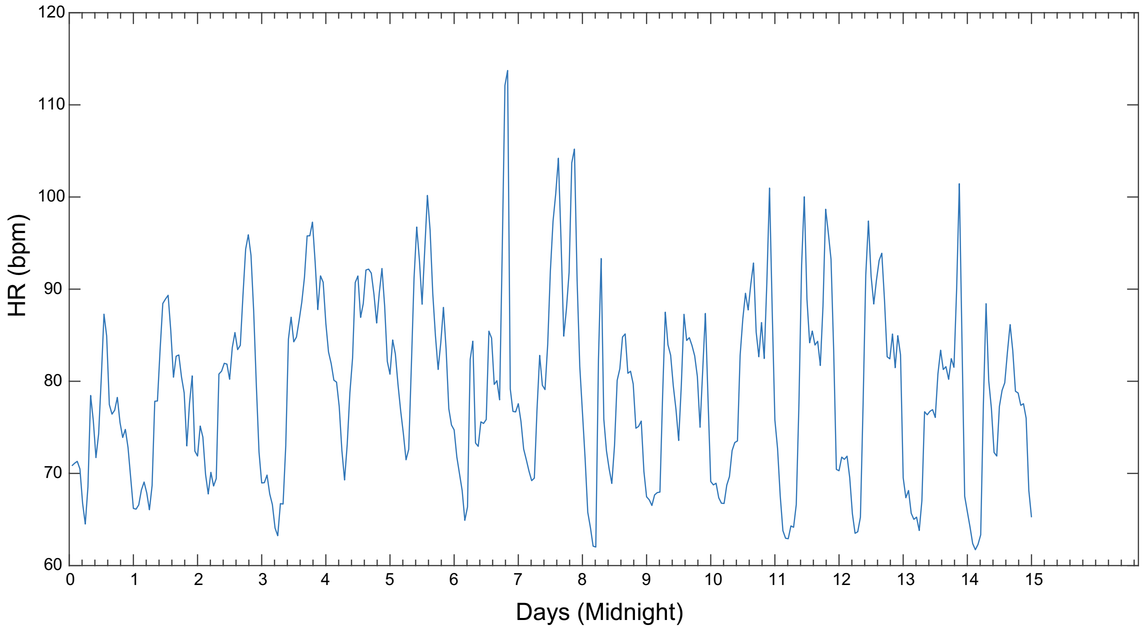

Fig. 2 Raw data time-series of the heart rate (beats per minute, bpm) of a sample subject. The clear manifestation of a circadian cycle demonstrates the success of the mobile monitoring technology in capturing the time-stamps of heartbeats.

Table 1 Correlations between HRV components (*$p < 0.001$, both with and without autocorrelation)

	HR	SDNN	HRVTi	RMSSD	VLF_{ratio}	LF_{ratio}	HF_{ratio}	LF/HF	Total Power
HR	1								
SDNN	−0.68*	1							
HRVTi	−0.67*	0.91*	1						
RMSSD	−0.69*	0.91*	0.80*	1					
VLF_{ratio}	0.37*	−0.33*	−0.36*	−0.52*	1				
LF_{ratio}	0.33*	−0.34*	−0.21*	−0.36*	−0.42*	1			
HF_{ratio}	−0.64*	0.61*	0.53*	0.82*	−0.67*	−0.39*	1		
LF/HF	0.58*	−0.58*	−0.50*	−0.66*	0.36*	0.43*	−0.72*	1	
Total Power	−0.59*	0.94*	0.80*	0.89*	−0.34*	−0.30*	0.59*	−0.51*	1

HR mean heart rate, VLF_{ratio} ratio of absolute VLF power to total power, LF_{ratio} ratio of absolute LF power to total power, HF_{ratio} ratio of absolute HF power to total power, *LF/HF* ratio of absolute LF power to absolute HF power, *total power* summation of absolute VLF, LF, and HF power. *$p < 0.001$

and reliable measure of solar activity (Tapping 2013). F10.7 is measured in solar flux units (sfu) and is often used as a proxy for other measures of solar activity.

Relationship of HRV components with geomagnetic activity

Uncorrected and corrected for autocorrelation correlation coefficients between HRV components and geomagnetic activity are presented (Tables 2, 3, 4). We found significant correlations of A_p index with HRVTi, VLF_{ratio}, LF_{ratio}, and HF_{ratio} before correction but no significant correlations between A_p index and HRV components after correction (all $p > 0.05$, Table 2). The *K*-index is significantly correlated with VLF_{ratio} and LF_{ratio} before correction, and the VLF_{ratio} correlation remained significant after correction, such that VLF_{ratio} increased as the local geomagnetic *K*-index increased ($r = 0.06$, $p < 0.05$, Table 3). We also found this relationship when excluding participants with time-corrected data, implying that timestamp errors were not the source of the effect ($r = 0.08$, $p < 0.01$). In addition, we found significant correlations of K_p-index with HR, RMSSD, VLF_{ratio}, LF_{ratio}, HF_{ratio}, LF/HF, and total power before correction, but no significant correlations after correction (all $p > 0.05$, Table 4).

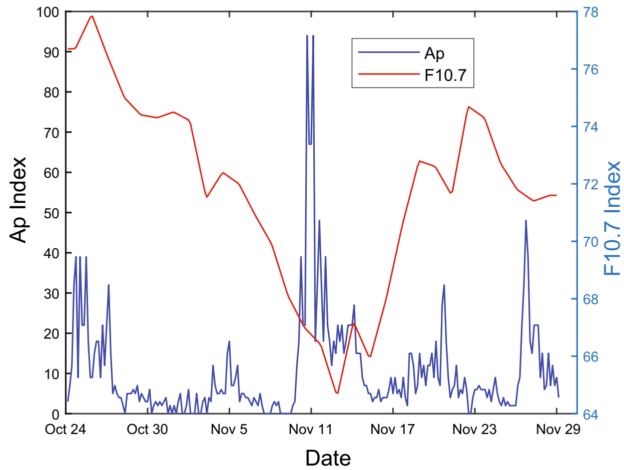

Fig. 3 Geomagnetic Ap index and solar F10.7 index for the study period. See Methods Section for data sources

A previous study (McCraty et al. 2017) computed correlations after dividing the recording timeline into three distinct periods based on the occurrence of a geomagnetic storm, finding different relationships during the storm than before and after. To investigate this proposed phenomenon, we divided the A_p index values into three groups. The first group was the bottom 10th percentile of A_p index values; all A_p index values here were 0, so this group was not further analyzed. The second group consisted of A_p index values between the 10th and 90th percentile (1–21), while the third group consisted of the top 90th percentile (22–94).

We calculated correlations between HRV components and AP index values for the two latter groups (Table 5). We found significant correlations between A_p index (top 90th percentile) and HRVTi, A_p index (10th–90th percentile) and HRVTi, VLF_{ratio}, LF_{ratio}, for uncorrected values. However, we found no significant correlations for corrected values.

Time-dependent relationship

To test for the potential presence of a time-lag between geomagnetic activity and change in HRV, we computed correlations between HRV components and corresponding A_p -index values 1 day after (anticipatory) and A_p-index values 1 day before (consequential). This analysis was motivated by previous studies (McCraty et al. 2017; Alabdulgader et al. 2018) that discussed a potential "anticipatory effect", which may relate to the fact that changes in solar activity take several days to modulate the geomagnetic field due to the time solar wind takes to reach the earth. In this analysis, we found a significant anticipatory relationship between heart rate and A_p index which survived the correction for autocorrelation of time-series; heart rate was negatively correlated with geomagnetic activity for corrected values (Table 6, $r = -0.09$, $p = 0.03$). To further explore this significant correlation between heart rate and A_p index (anticipatory), we calculated correlations for each individual participant, again with and without correction for autocorrelation. Out of the 19 participants, 14 participants exhibited a negative correlation. In terms of significance testing, there were eight

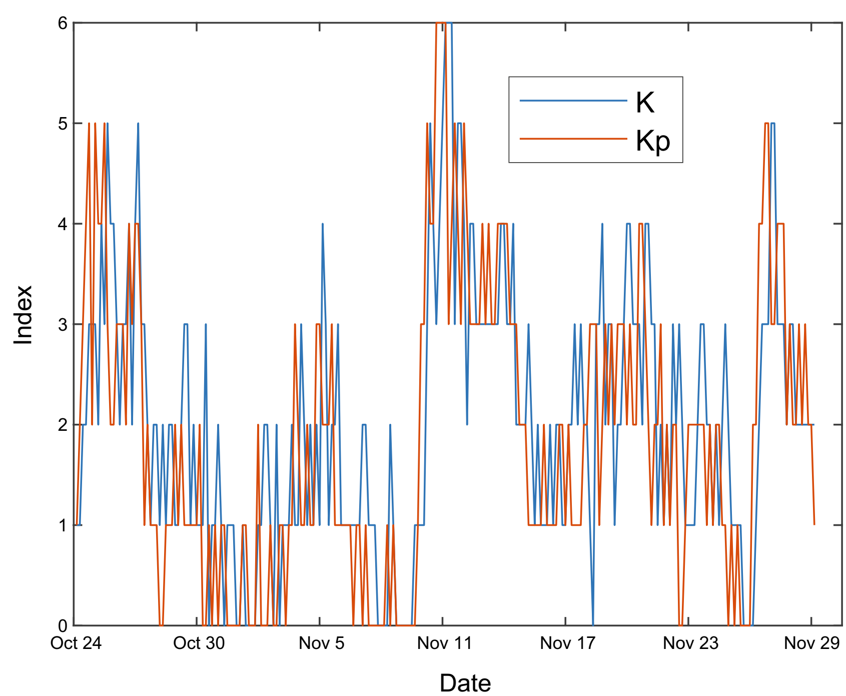

Fig. 4 Geomagnetic K (Local, Boulder, CO) and Kp (Global) indices for the study period. See Methods Section for data sources

Table 2 Correlation coefficients and *p*-values between HRV components and Ap index

	Ap index		
	r-value	*p*-value (uncorrected)	*p*-value (corrected)
HR	−0.01	0.40	0.76
SDNN	0.01	0.34	0.65
HRVTi	0.03	**0.03***	0.34
RMSSD	−0.01	0.42	0.74
VLF_{ratio}	0.06	**<0.001****	0.08
LF_{ratio}	−0.03	**0.05***	0.33
HF_{ratio}	−0.03	**0.04***	0.42
LF/HF	0.03	0.07	0.49
Total power	−0.01	0.40	0.68

Uncorrected and corrected *p*-values are presented. $*p<0.05$, $**p<0.001$

Table 4 Correlation coefficients and *p*-values between HRV components and K_p index

	K_p index		
	r-value	*p*-value (uncorrected)	*p*-value (corrected)
HR	0.002	**<0.001****	0.95
SDNN	−0.001	0.06	0.98
HRVTi	0.0001	0.30	0.98
RMSSD	−0.002	**<0.001****	0.95
VLF_{ratio}	0.002	**<0.001****	0.95
LF_{ratio}	0.001	**0.04***	0.98
HF_{ratio}	−0.003	**<0.001****	0.95
LF/HF	0.002	**<0.001***	0.96
Total power	−0.001	**0.01***	0.97

Uncorrected and corrected *p*-values are presented. $*p<0.05$, $**p<0.001$

Table 3 Correlation coefficients and *p*-values between HRV components and *K* index (Boulder, CO, magnetometer)

	K index		
	r-value	*p*-value (uncorrected)	*p*-value (corrected)
HR	0.02	0.25	0.63
SDNN	−0.01	0.93	0.77
HRVTi	0.02	0.30	0.54
RMSSD	−0.03	0.07	0.41
VLF_{ratio}	0.06	**<0.001****	**0.045***
LF_{ratio}	−0.04	**0.01***	0.21
HF_{ratio}	-0.03	0.08	0.44
LF/HF	0.01	0.34	0.78
Total power	−0.03	0.08	0.33

Uncorrected and corrected *p*-values are presented. $*p<0.05$, $**p<0.001$

individuals with a significant correlation (all negative values) before correction for autocorrelation and three of these individuals exhibited a significant correlation after correction (Table 7).

Relationship of HRV with solar activity

For solar activity (F10.7 index), we found significant correlations between F10.7 index and SDNN, HRVTi, LF_{ratio}, HF_{power}, HF_{ratio}. However, all significant effects were lost after correction for autocorrelation (Table 8). Of note, F10.7 index is a more direct measure of several solar processes and does not have a time-lag that A_p index may exhibit, which reflects changes in the geomagnetic field as a result of solar processes.

Discussion

In this study, we investigated how geomagnetic/solar activity affects human HRV. We collected 720 h of HRV data from 19 participants and obtained geomagnetic and solar activity. Previous studies found significant, strong correlations between HRV and geomagnetic activity (McCraty et al. 2017; Alabdulgader et al. 2018). In seeming agreement with this previous work, we also found significant correlations between the two type of variables before correction for the autocorrelation inherent to time-series. After correction for autocorrelation, however, we only found a significant correlation between very low-frequency power of HRV and *K* index and a significant anticipatory effect on heart rate with A_p index. Our results suggest that previous findings may be a consequence of autocorrelation instead of a true relationship between geomagnetism and HRV. We thus strongly recommend that correct statistical analyses should be performed when investigating this relationship.

Inspired by previous findings of time-dependent effects of geomagnetic activity on HRV (Dimitrova et al. 2013; McCraty et al. 2017), we also examined potential relationships with an offset of one day in both anticipatory or consequential manners. As a result, we found a significant relationship of an anticipatory effect such that heart rate was lower the day before the higher geomagnetic activity, though the correlation was weak ($r=-0.09$). Another study that examined time-dependent effects did not find this relationship to be significant (Dimitrova et al. 2013). While this

Table 5 Correlation coefficients and *p*-values between HRV components and percentiles of A_p index

	Top 90th percentile			10–90th percentile		
	r-value	*p*-value (uncorrected)	*p*-value (corrected)	*r*-value	*p*-value (uncorrected)	*p*-value (corrected)
HR	−0.02	0.65	0.80	0.02	0.30	0.64
SDNN	−0.07	0.10	0.38	0.01	0.46	0.70
HRVTi	−0.08	**0.04***	0.34	0.05	**0.01***	0.18
RMSSD	−0.02	0.58	0.82	−0.01	0.47	0.72
VLF_{ratio}	0.01	0.72	0.84	0.04	**0.02***	0.21
LF_{ratio}	0.00	0.93	0.84	−0.05	**0.01***	0.20
HF_{ratio}	−0.02	0.62	0.75	0.00	0.83	0.92
LF/HF	0.08	0.06	0.29	0.00	0.82	0.92
Total power	−0.06	0.13	0.56	−0.02	0.24	0.49

Uncorrected and corrected *p*-values are presented. $^*p<0.05$

Table 6 Time-dependent effect of A_p index with HRV components

	Anticipatory			Consequential		
	r-value	*p*-value (uncorrected)	*p*-value (corrected)	*r*-value	*p*-value (uncorrected)	*p*-value (corrected)
HR	−0.09	**<0.001****	**0.03***	−0.02	0.70	0.89
SDNN	0.02	0.24	0.65	−0.07	0.22	0.59
HRVTi	0.01	0.44	0.73	−0.08	**<0.001****	0.08
RMSSD	0.05	**<0.001****	0.63	−0.02	0.14	0.81
VLF_{ratio}	−0.03	**0.03***	0.25	0.01	0.15	0.48
LF_{ratio}	−0.03	**0.03***	0.27	0.01	0.29	0.61
HF_{ratio}	0.06	**<0.001****	0.09	−0.02	**0.02***	0.35
LF/HF	−0.01	0.64	0.85	0.08	0.74	0.91
Total power	−0.003	0.84	0.92	−0.06	0.62	0.80

Correlation coefficients and uncorrected and corrected *p*-values are presented. $^*p<0.05$, $^{**}p<0.001$

result possibly warrants further examination due to the various health abnormalities in which geomagnetism has been implicated (Dimitrova et al. 2004, 2013; Stoupel 2006), we note the possibility of a false positive considering the small effect size and the large amount of relationships tested to find this single result. For this effect to exist, the body would require a mechanism to predict geomagnetic storms. It is possible that the body detects abnormalities in geomagnetic fields before a sharp increase, or directly responds to changes in solar activity that reaches the earth before the factors that modulate the geomagnetic field. However, we would expect a significant relationship with solar activity to have existed if this was the case. Before further mechanistic speculation or examination, we recommend additional study replication, as this is the first study to find this specific effect. Since we did not record any behavioral data in our study, we are unable to provide a mechanistic understanding of how solar and geomagnetic activity could alter HRV. This present study does not preclude the potential existence of a causal chain between solar and geomagnetic activity, cognition and behavior, modulation of the autonomic nervous system, and HRV markers. Instead, our study emphasizes the importance of using stringent controls of potential confounding factors such as the role of autocorrelation when computing the correlation of two time-series.

As the intensity of geomagnetism varies with latitude, we also correlated HRV indices with the local geomagnetic *K* index from the Boulder magnetometer. After correction for autocorrelation, we found a relationship between the local *K* index and VLF_{ratio} such that the VLF band was stronger during stronger local geomagnetic activity. This finding may have clinical implications, as low VLF power has been more linked to all-cause mortality than the LF and HF bands (Mccraty and Shaffer 2015), though we again note the weak correlation ($r=0.06$) and the possibility of a false positive. We also note that VLF is poorly resolved in 5-min recordings studied here and this result may be an indication of long-term effects not examined.

Table 7 Individual anticipatory relationship of heart rate and A_p index

Participant #	Sex	Age	Anticipatory effect (A_p index and heart rate)		
			r-value	*p*-value (uncorrected)	*p*-value (corrected)
P01	Male	20	0.05	0.43	0.62
P02	Male	20	−0.14	**0.04***	0.23
P03	Female	21	−0.25	**< 0.01***	0.08
P04	Female	20	−0.11	0.13	0.37
P05	Male	33	−0.01	0.97	0.98
P06	Female	20	−0.39	**< 0.001****	**0.01***
P07	Female	19	−0.01	0.92	0.95
P08	Female	21	−0.27	**< 0.001****	**0.03***
P09	Female	20	−0.14	**0.03***	0.19
P10	Female	18	0.07	0.28	0.56
P11	Female	24	−0.17	**< 0.01***	0.14
P12	Female	20	0.08	0.27	0.50
P13	Female	48	0.03	0.70	0.80
P14	Female	64	−0.16	**0.01***	0.17
P15	Male	37	−0.03	0.64	0.78
P16	Male	23	0.04	0.50	0.69
P17	Excluded (please see section "Methods")				
P18	Male	25	−0.01	0.85	0.90
P19	Male	31	−0.31	**< 0.001****	**< 0.001****
P20	Male	31	−0.11	0.09	0.33

Demographics, correlation coefficients, and *p*-values are presented. *$p < 0.05$, **$p < 0.001$

Table 8 Relationship of HRV with solar activity

	F10.7 index		
	r-value	*p*-value (uncorrected)	*p*-value (corrected)
HR	0.04	**< 0.001****	0.30
SDNN	−0.03	**0.01***	0.48
HRVTi	−0.04	**< 0.001****	0.31
RMSSD	−0.01	0.39	0.85
VLF_{ratio}	−0.05	**< 0.001****	0.11
LF_{ratio}	0.04	**< 0.001****	0.25
HF_{ratio}	0.02	**0.01***	0.57
LF/HF	−0.01	0.37	0.84
Total power	−0.01	0.41	0.82

Correlation coefficients and *p*-values are presented. *$p < 0.05$, **$p < 0.001$

As a secondary focus, we report the effects of solar activity on HRV components. Similar to geomagnetic activity, solar activity has previously been correlated to SDNN, total power, LF, HF, VLF, and the LF/HF ratio (McCraty et al. 2017; Alabdulgader et al. 2018). Again contrasting the results of previous studies, we found no significant relationships between HRV components and solar index F10.7. It is possible that no significant effects were found due to the 20-participant sample size or the 1-month recording period. A study (McCraty et al. 2017) reported significant relationships with very strong effect sizes, with some R^2 values, such as the one between LF power and F10.7 index, reaching as high as 0.76. Results presented here vastly differ from this previous research, as we only found one significant relationship, which was small in magnitude. Noting the multitude of significant correlations that we found before accounting for autocorrelation, the difference between this study and previous studies likely stems from the choice of the procedure to determine statistical significance. Time-series correlated against each other may inherently be correlated as subsequent data points are dependent on each other, and the possible impact of this effect on studies examining environmental effects on HRV was pointed out in a Discover Magazine blog (Neuroskeptic 2018). Since all but one correlation lost significance after autocorrelation was removed, this study suggests that there is little to no relation between solar or geomagnetic activity and HRV, and contrasting findings are likely a result of the interdependence of data analyzed. It is unlikely that our test for autocorrelation erroneously removed significant relationships, as all correlations between HRV components (Table 1) survived the autocorrelation correction.

It is worth noting that there is an entire body of research on what is referred to as heliobiology. The full discussion of this literature is beyond the scope of this paper since many

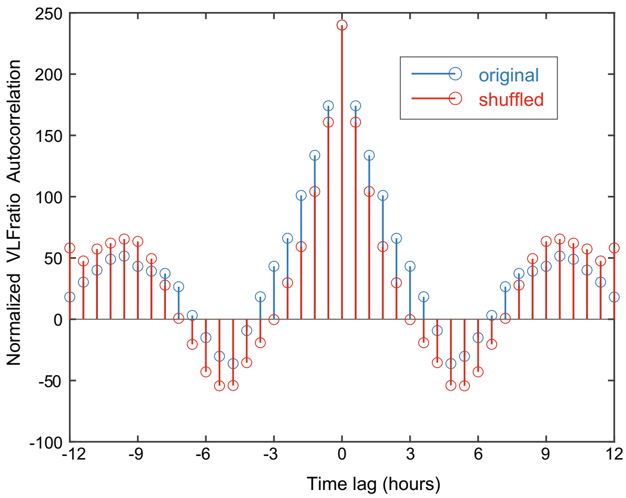

Fig. 5 Autocorrelation plot for original and shuffled VLF_{ratio} data. *X* and *y*-axis indicate time lags (hours) and normalized VLF_{ratio} autocorrelation

of the studies appear to exhibit serious flaws in methodology and reports (Palmer et al. 2006). The potential mechanism of action remains speculative. In addition, there are other complicating factors in this research field, which include that the 11-year solar cycle makes studies hard to compare. For example, our study was performed near the nadir of the current solar cycle (near end of Cycle 24). In addition, geographic latitude is likely to matter, and results may strongly depend on the latitude of the study site. Finally, it cannot be excluded that there are strongly differing levels of sensitivities across otherwise homogenous study populations. Our participant-by-participant analysis appears to support such individual differences in sensitivities to geomagnetic perturbations.

As any scientific study, our work has several limitations. First, larger sample sizes are desirable and warranted based on our results. Second, we tested numerous relationships and the few results that were significant at the $p < 0.05$ level were weak correlation values ($r < 0.09$), possibly indicating that the results are false positives. It is important that the statistical significance of these two findings are considered in the context of multiple comparisons inherent to exploratory analyses. Importantly, statistical significance does not imply biological significance or plausibility. Third, we have not collected any other psychological or biological variables which may explain the individual differences we found for the anticipatory relationship between heart rate and geomagnetic activity. Fourth, post-hoc analysis of VLF_{ratio} showed that the autocorrelation function from shuffled data differed from that of the original data before a time-lag of 3 h, indicating that the desired autocorrelation within HRV indices was not entirely preserved (Fig. 5). This limitation is inherent to such shuffling approaches and should be taken into consideration when interpreting the results of this study. Finally, our data set included missing data since the technology used to track heart rate does not allow for uninterrupted measurements during activities where the sensors get wet. The resulting missing data are typical for such naturalistic studies that collect data outside the laboratory. Nevertheless, we cannot exclude the theoretical possibility that the missing data has biased our results.

Overall, our study suggests that there is little to no effect of solar or geomagnetic activity on heart rate variability, with the only significant relationships being an anticipatory decrease in heart rate before increased global geomagnetic activity and an increase in very low-frequency power during periods of higher local geomagnetic activity. As in any research field, a single study does not provide final answers and more studies are warranted given the number of epidemiological studies that implicate solar/geomagnetic activity in human health. Possible extensions of this study include segmenting data into day/night cycles to further explore potential effects and analyzing long-term HRV rather than the short-term HRV studied here.

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Author contributions MM, CF, and FF designed the experiments; MM collected data; MM and SA analyzed the data; MM, SA, CF, and FF prepared the manuscript.

Compliance with ethical standards

Conflict of interest There is no conflict of interest.

References

Alabdulgader A, McCraty R, Atkinson M et al (2018) Long-term study of heart rate variability responses to changes in the solar and geomagnetic environment. Sci Rep 8:2663. https://doi.org/10.1038/s41598-018-20932-x

Baek HJ, Cho C-H, Cho J, Woo J-M (2015) Reliability of ultra-short-term analysis as a surrogate of standard 5-min analysis of heart rate variability. Telemed e-Health 21:404–414. https://doi.org/10.1089/tmj.2014.0104

Baevsky RM, Petrov VM, Cornelissen G et al (1997) Meta-analyzed heart rate variability, exposure to geomagnetic storms, and the risk of ischemic heart disease. Scr Med (Brno) 70:201–206

Bakdash JZ, Marusich LR (2017) Repeated measures correlation. Front Psychol 8:456. https://doi.org/10.3389/fpsyg.2017.00456

Blood JD, Wu J, Chaplin TM et al (2015) The variable heart: High frequency and very low frequency correlates of depressive symptoms in children and adolescents. J Affect Disord 186:119–126. https://doi.org/10.1016/j.jad.2015.06.057

Buccelletti E, Gilardi E, Scaini E et al (2009) Heart rate variability and myocardial infarction: systematic literature review and metanalysis. Eur Rev Med Pharmacol Sci 13:299–307

Chernouss S, Vinogradov A, Vlassova E (2001) Geophysical hazard for human health in the circumpolar auroral belt: evidence of a relationship between heart rate variation and electromagnetic disturbances. Nat Hazards 23:121–135. https://doi.org/10.1023/A:1011108723374

Dimitrova S, Stoilova I, Yanev T, Cholakov I (2004) Effect of local and global geomagnetic activity on human cardiovascular homeostasis. Arch Environ Heal An Int J 59:84–90. https://doi.org/10.3200/AEOH.59.2.84-90

Dimitrova S, Angelov I, Petrova E (2013) Solar and geomagnetic activity effects on heart rate variability. Nat Hazards 69:25–37. https://doi.org/10.1007/s11069-013-0686-y

Harris PA, Taylor R, Thielke R et al (2009) Research electronic data capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. J Biomed Inform 42:377–381. https://doi.org/10.1016/j.jbi.2008.08.010

Klinkenberg AV, Nater UM, Nierop A et al (2009) Heart rate variability changes in pregnant and non-pregnant women during standardized psychosocial stress. Acta Obstet Gynecol Scand 88:77–82. https://doi.org/10.1080/00016340802566762

Krygier JR, Heathers JAJ, Shahrestani S et al (2013) Mindfulness meditation, well-being, and heart rate variability: a preliminary investigation into the impact of intensive Vipassana meditation. Int J Psychophysiol 89:305–313. https://doi.org/10.1016/j.ijpsycho.2013.06.017

Louis S, Borgelt C, Grün S (2010) Generation and selection of surrogate methods for correlation analysis. Analysis of parallel spike trains. Springer, Berlin, pp 359–382

Neuroskeptic (2018) Solar silliness: the heart–sun connection. Discov Mag

Malik M, Camm AJ (1990) Heart rate variability. Clin Cardiol 13:570–576. https://doi.org/10.1002/clc.4960130811

McCraty R, Atkinson M, Stolc V et al (2017) Synchronization of human autonomic nervous system rhythms with geomagnetic activity in human subjects. Int J Environ Res Public Health 14:770. https://doi.org/10.3390/ijerph14070770

Mccraty R, Shaffer F (2015) Heart rate variability: new perspectives on physiological mechanisms, assessment of self-regulatory capacity, and health risk. Glob Adv Heal Med 4:46–61. https://doi.org/10.7453/gahmj.2014.073

Monfredi O, Lyashkov AE, Johnsen A-B et al (2014) Biophysical characterization of the underappreciated and important relationship between heart rate variability and heart rate. Hypertension 64:1334–1343. https://doi.org/10.1161/HYPERTENSIONAHA.114.03782

Montano N, Porta A, Cogliati C et al (2009) Heart rate variability explored in the frequency domain: a tool to investigate the link between heart and behavior. Neurosci Biobehav Rev 33:71–80

Nakamura T, Small M (2005) Small-shuffle surrogate data: testing for dynamics in fluctuating data with trends. Phys Rev E Stat Nonlinear Soft Matter Phys. https://doi.org/10.1103/PhysRevE.72.056216

Ori Z, Monir G, Weiss J et al (1992) Heart rate variability: frequency domain analysis. Cardiol Clin 10:499–533

Palmer SJ, Rycroft MJ, Cermack M (2006) Solar and geomagnetic activity, extremely low frequency magnetic and electric fields and human health at the Earth's surface. Surv Geophys 27:557–595. https://doi.org/10.1007/s10712-006-9010-7

Shaffer F, McCraty R, Zerr CL (2014) A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. Front Psychol 5:1040. https://doi.org/10.3389/fpsyg.2014.01040

Small M, Tse CK (2003) Detecting determinism in time series: the method of surrogate data. IEEE Trans Circuits Syst I Fundam Theory Appl 50:663–672. https://doi.org/10.1109/TCSI.2003.811020

Stoupel E (2006) Cardiac arrhythmia and geomagnetic activity. Indian Pacing Electrophysiol J 6:49–53

Sztajzel J (2004) Heart rate variability: a noninvasive electrocardiographic method to measure the autonomic nervous system. Swiss Med Wkly 134:514–522

Tapping KF (2013) The 10.7 cm solar radio flux (F10.7). Sp Weather 11:394–406. https://doi.org/10.1002/swe.20064

Tarvainen MP, Niskanen J-P, Lipponen JA et al (2014) Kubios HRV—heart rate variability analysis software. Comput Methods Progr Biomed 113:210–220. https://doi.org/10.1016/J.CMPB.2013.07.024

Watanabe Y, Cornélissen G, Halberg F et al (2001) Associations by signatures and coherences between the human circulation and helio- and geomagnetic activity. Biomed Pharmacother 55(Suppl 1):76s–83s

Yang AC, Hong C-J, Tsai S-J (2010) Heart rate variability in psychiatric disorders