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# Global study of long term heart rhythm synchronization in groups

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**Heart rhythm measurements over time reflect important elements of Autonomic Nervous System dynamics. Synchronization among the heart rhythms of multiple participants has been observed, but this study uses the first global dataset collected that measures synchronization at several locations across the globe continuously for multiple weeks. For 15 days, 104 participants located in California (USA), Lithuania, Saudi Arabia, New Zealand, and England underwent continuous ambulatory heart rhythm monitoring. They were not instructed to perform tasks together. Significant long-term correlations were observed across participants within the same region, for just the groups in Saudi Arabia and New Zealand. This is surprising, given that each participant has an individualized life and distinct heart rate. In a different analysis using population-mean cosinor, only in these two locations was a significant circaseptan (about 7-day) rhythm observed. It appears that weekly rhythms in these groups partially contribute to correlations, in addition to long-term movements. A hypothesis with supporting evidence is proposed to explain this, that participants in these groups were socially closer than in the other groups. It would then appear that heart rhythms synchronize over the long term due to social connectedness, even when they are not physically near each other or performing tasks together.**

**Keywords** Heart rate variability, HRV, Autonomic nervous system, Social connection, Synchronization, Circaseptan (about 7-day) rhythm

Evolutionary anthropology research posits that a key driver of human species evolution lies in our advanced capacities for social interaction and cooperation[1,2]. This body of work further suggests that the human inclination for seeking social connections and forming secure attachments is hard-wired, transcending maturational stages and cultural influences[3]. Throughout life, individuals dedicate a significant portion of their time to communication, interaction, and collaborative tasks with others. Membership in diverse groups becomes an inherent and often sought-after aspect of our existence. Intimate connections, considered some of life's most cherished moments, underscore the intrinsic human desire for social bonds. Terminologies such as social coherence, social support, social connection, social functioning, loneliness, and social isolation encompass the multifaceted dimensions of human social functioning. Social or group coherence relates to pairs, families, groups or larger organizations in which there is a stable and harmonious alignment of relationships that allow for an efficient flow and utilization of energy and communication required for optimal collective action[4].

The importance of developing skills and behaviors and being able to successfully connect, cooperate and collaborate with others is of great importance because it fosters effective communication, builds strong interpersonal relationships, and creates a foundation for collective problem-solving and innovation. This ability not only enhances individual well-being but also contributes significantly to the success of teams, organizations, and communities, ultimately shaping a more harmonious and interconnected society.

When social organization is incoherent and relations are discordant, optimal or even basic coordinated action may not be possible and psychosocial instability and dysfunction are likely consequences[5]. Disruption in social coherence goes beyond influencing our emotions, relationships, and communication; it also has a significant impact on physiological processes, leading to potential health issues. Remarkably, in the realm of public health, fostering social coherence and connections emerges as a critical priority. This importance is underscored by the impactful research of James Lynch, revealing that loneliness poses a greater risk for heart disease than the combined effects of factors such as lack of exercise, smoking, excessive alcohol consumption, and obesity[6]. Other studies link social coherence to a reduced risk of mortality and disease and more content and healthier lives[7–10].

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The smoothness or flow in social interactions depends largely on interpersonal synchrony, which is defined as the spontaneous rhythmic and temporal coordination of actions, emotions, thoughts and physiological processes between two or more participants[11]. During conversations, individuals instinctively synchronize not only their movements, vocal pitch, postures, and speaking rates but also the intervals between responses, as observed by Hatfield[12]. Interestingly, recent revelations indicate that physiological aspects also undergo synchronization during such interactions. Numerous studies have delved into diverse forms of physiological synchronization within infants, pairs, and groups, shedding light on the intricacies of this phenomenon.

For the physiological activity of distinct individuals to synchronize, some form of signal, whether it be electromagnetic waves, sound, tactile sensations, quantum mechanical, or chemical, must facilitate the exchange of information between them[13,14]. For instance, the visual coordination of physical movements has been linked to heightened feelings of affiliation[15], increased self-esteem[16], enhanced compassion and altruistic behavior[17] strengthened rapport[18], and a rise in pro-social behavior[19]. Conversely, during arguments, synchrony tends to decrease[20]. Studies reveal that in group settings, synchronization fosters increased conformity[21], cooperation, trust[22] and the fortification of social bonds among group members[22].

In the realm of social neuroscience, there is a growing fascination with the significance of synchronized brain activity among individuals and within groups[23–26]. Yet, the exploration of brain synchronization during real-world social interactions faces considerable challenges, mainly stemming from methodological limitations. This is primarily attributed to the scarcity of well-equipped, time-synchronized recording setups that allow simultaneous data collection from two or more individuals and the absence of adequate tools for conducting multi-subject analyses.

## Heart rhythm synchronization as a measure of interaction synchrony

Another method for assessing interaction synchrony between individuals involves examining the synchronization of heart rhythms and Heart Rate Variability (HRV). HRV serves as a real-time indicator of Autonomic Nervous System (ANS) dynamics and possesses the practical and technical capacity to monitor multiple participants simultaneously[13]. This makes it an ideal tool for investigating real-time dynamics during group interactions and physiological synchronization. Notably, HRV holds the advantage of potentially reflecting participants' emotional states during various interactions. State-specific patterns in HRV waveforms, indicative of real-time emotions like frustration, anger, anxiety, and appreciation, can be frequently identified. Importantly, these patterns are independent of the overall HRV quantity in an individual[27]. Independent research has even demonstrated a 75% accuracy in identifying discrete emotional states from HRV waveforms using machine learning for pattern recognition[28]. The immediate manifestation of emotional states in the HRV pattern is likely attributed to changes in the outputs of subcortical structures involved in emotion processing, as described by Pribram[29], Porges[30] and Thayer[31], where subcortical structures influence the oscillatory output of the cardiorespiratory centers in the brainstem. Utilizing HRV as a measure allows for the simultaneous assessment of physiological synchronization and the emotional experiences occurring during interactions.

Recent research has underscored the profound impact of social closeness on physiological synchrony, particularly through measures such as Heart Rate Variability (HRV). Studies, such as those conducted by Feldman, have shown that during face-to-face interactions, a mother unconsciously adapts her heart rhythms to those of her infant, and the infant adapts his or her heart rhythms to those of the mother in less than a second, resulting in a biological synchronization between the accelerations and decelerations of their heart rates. The highest degree of HRV synchronization occurred when emotional synchrony took place, while gaze synchronization did not increase HRV synchronization[32]. The findings of this line of research led Feldman to suggest that biological rhythms provide the foundation for social rhythms[33].

In an exploration of physiological synchronization during nonverbal compassionate communication, Kemper and Shaltout identified significant changes in the receiver's autonomic nervous system, correlating with the sender's[34]. Investigating heart rhythm synchrony in couples during sleep, Yoon et al. discovered that in co-sleepers, independent heart rhythms not only exhibited the same relative phase for extended periods but also demonstrated a bidirectional causal relationship[35]. Ogolsky et al.'s study on older married couples over a two-week period found that correlations in the couples' heart rhythms were associated with proximity and interaction dynamics, illustrating that partners' heart rates are dynamically intertwined in meaningful ways[36].

Russek and Schwartz observed cardiac-related information exchange between individuals, with greater physiological synchronization in people raised in a loving environment[37]. Lin et al.'s recent investigation into emotional contagion revealed that friend dyads exhibited greater heart rate and HRV synchrony compared to stranger dyads[11]. However, Bizzego et al. found that during passive social activities without interaction requirements, HRV synchrony did not necessarily reflect relationship closeness between partner pairs. Instead, synchrony appeared more pronounced between strangers, suggesting increased effort to establish new social affiliations[38].

An interesting study that also suggests social closeness impacts was conducted during a ceremony that looked at synchronized heart rhythms between firewalkers and spectators[39]. During a 30-minute ceremony, they found a high degree of synchronized activity between the firewalkers and spectator's HRV who had an emotional connection to them. The unrelated spectators who did not have an emotional connection to the firewalkers did not have HRV synchronization with the firewalkers. The researchers concluded that the mediating mechanism must be information that was somehow distributed among the group members.

Directly relevant to this study, the degree of HRV synchronization was evaluated among a group of 20 individuals and changes in the Earth's magnetic field, along with meaningful social interrelationships measures among the participants. This resulted in clusters of similar synchronization patterns over a two-week period. The study also confirmed the existence and synchronization of slow-wave dynamic patterns in the HRV rhythms between participant clusters. The slow-wave rhythms in heart rate variability can synchronize with changes in local magnetic field data, and the degree of synchronization is affected by the quality of interpersonal relationships[40].

These findings emphasize the intricate interplay between social connections and physiological states, shedding light on the importance of social closeness in fostering not only emotional resonance but also a tangible physiological coherence among individuals. Understanding these dynamics is not only relevant in the realms of psychology and sociology but also holds implications for promoting overall well-being and building stronger, more connected communities in our social fabric.

### International HRV synchronization study

This study is the next analysis in a larger study called the International HRV Synchronization Study. As far as we are aware, this is the first global dataset collected that measures synchronization at several locations across the globe continuously for multiple weeks. We previously published a study of this data, which used attractor embedding techniques to observe HRV synchronization with the Earth's time varying magnetic field data. This included a 15-minute period on one of the days in which all participants were instructed to perform a Heart-focused meditation exercise known to increase HRV coherence. During the meditation period, there was a significant increase in HRV coherence and synchronization between the group participants and it was also found on that day alone that all of the groups' HRV was positively correlated with the Earth's magnetic field data[41]. The meditation period was similar to most synchronization studies, in which the participants are instructed to perform some type of task or activity together over a limited time interval in order to generate synchronization.

This paper expands the scope of the analysis to investigate long-term HRV synchronization among the groups of participants in the form of cross correlations that persist over the full two-week period. Aside from the 15-minute exercise, the participants were not instructed to perform any particular tasks together or at the same time. This analysis was intended to explore whether there was long-term HRV synchronization across the participants, and whether known correlates such as geomagnetic fields or social closeness may explain this.

## Results

The average inter-beat interval (IBI), the standard metric of heart rate, is shown across participants in each region in Fig. 1. Significant synchronization was observed across participants within the same regions, for just the groups in Saudi Arabia and New Zealand. This was measured as long-term correlations among their IBIs, with statistical significance being determined by a cyclic rotation analysis. The results for all 5 regions are shown in Table 1, with the p-values being significant for long-term correlation only in Saudi Arabia and New Zealand.

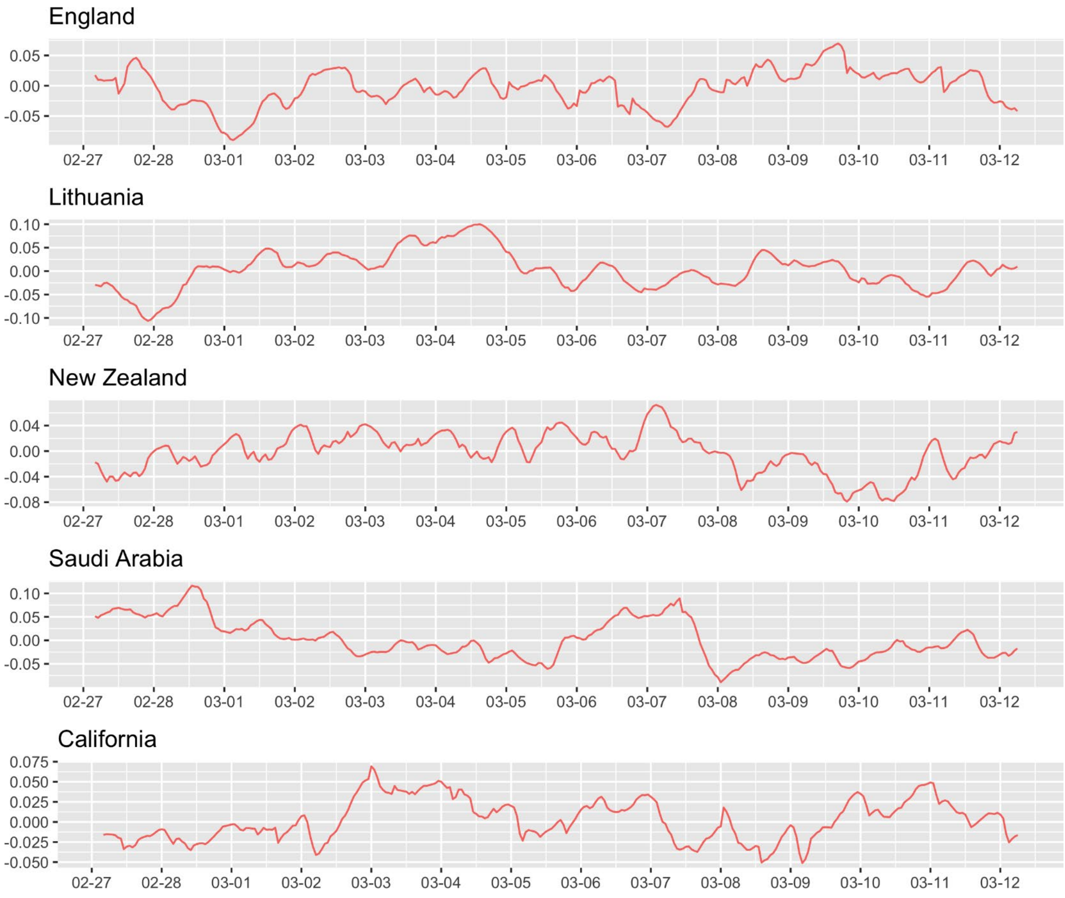

**Fig. 1**. Normalized average IBI with 24-hour moving average smoothing.

| Region | Long-term correlations | | Circaseptan component | |
|---|---|---|---|---|
| | Correlation | P-value | Amplitude | P-value |
| Saudi Arabia | 0.52 | **0.002**** | 11.7 | **0.02*** |
| New Zealand | 0.45 | **0.005**** | 7.8 | **0.04*** |
| Lithuania | 0.27 | 0.07 | 7.7 | 0.19 |
| England | 0.19 | 0.14 | 3.8 | 0.46 |
| California | 0.04 | 0.45 | 7.1 | 0.14 |

**Table 1**. (left) long-term correlations among participants, as measured by regional mean correlations and one-tailed p-values determined through a cyclic rotation analysis. (Right) Circaseptan component of regional mean IBIs, as measured by amplitude and p-values from zero-amplitude (no rhythm) test, determined through a population mean cosinor analysis. Significant values are shown in bold, with p-value significance levels: $^{*}p < 0.05$, $^{**}p < 0.01$.

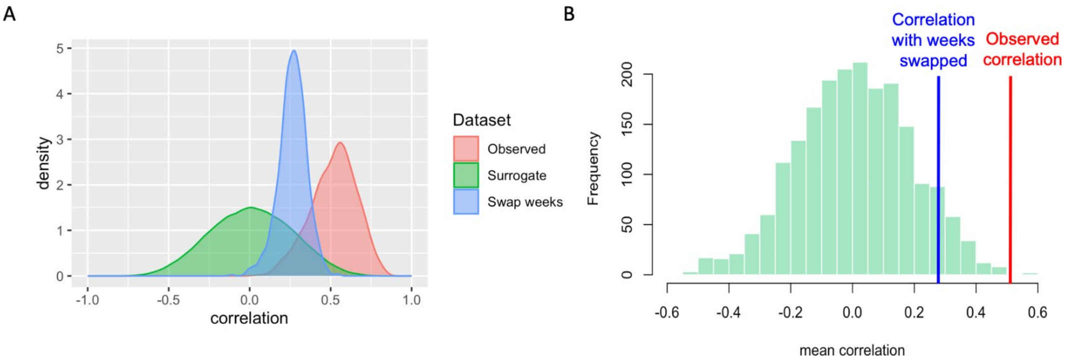

**Fig. 2**. Distributions of correlation data for heart rhythms in the Saudi Arabia group. (**A**) Density plots of correlations for observed vs. surrogate vs. swapped week distributions. The observed distribution (red) off to the right is generated from 1000 random split-half choices among the participants. The swapped week distribution (blue) closer to the center is generated from the same 1000 choices but with the first and second week swapped in the second half of the split. The surrogate distribution (green) in the center is generated from 1000 permutations of the HRV data, each with 100 split-half choices. (**B**) Histogram of regional *mean* correlations for the surrogate distribution, taking the mean over split-half choices. The red vertical line indicates the level of the observed regional mean correlation of 0.52 i.e. the mean of the observed distribution in pane A. It falls far in the tail and is less probable by chance than more than 99% of permutations to the left of the vertical line. The blue vertical line indicates the level of the regional mean correlation of 0.27 after swapping weeks, and it falls in the tail but not significantly.

To clarify how these significant correlations were determined, Fig. 2a shows results for Saudi Arabia as an example. The observed correlations are clearly positive, as compared to the surrogate distribution generated by cyclic permutation of the data, in which correlations center around zero. Figure 2b shows that the resulting regional mean correlation for this group is 0.52, exceeding that of most permutations and yielding a significant p-value less than 0.01.

A further analysis was performed to shed light on the extent to which weekly or residual circadian rhythms directly cause the long-term correlations that were observed. The split half approach was again applied to the observed dataset, but this time in each iteration one of the halves was shifted by one week; the first and second week were swapped. The expectation is that this would remove long-term behavior while keeping weekly or circadian rhythms intact. This results in a distribution of correlations that are weaker but still positive, as shown for Saudi Arabia in Fig. 2a. Figure 2b shows that the mean of these weaker correlations is 0.27, which alone is not significant. However, the observed dataset, which preserves both weekly and long-term rhythms, showed significant correlations. It appears that weekly rhythms contribute to the correlations in the observed dataset, in addition to the long-term movements of the timeseries.

This synchronization can be explained by consistent long-term behavior in the HRV of many participants in the same region. This is shown for two examples in Fig. 3. The consistency is clearest in the case of Saudi Arabia, where the time series have a similar trend, regardless of how we split the participants. By averaging the IBI's of several participants, a consistent trend is visible: IBI starts with a Saturday peak, trends downwards during the first week, then peaks over the next few days of the weekend, and in the final days trends more gradually upwards. There is a consistent long-term trend, in addition to a weekly recurrence of peaking on Saturday. In contrast, groups like the one in California do not show a consistent underlying time series; when the IBI is averaged across several participants, the trend is different depending on which participants are chosen.

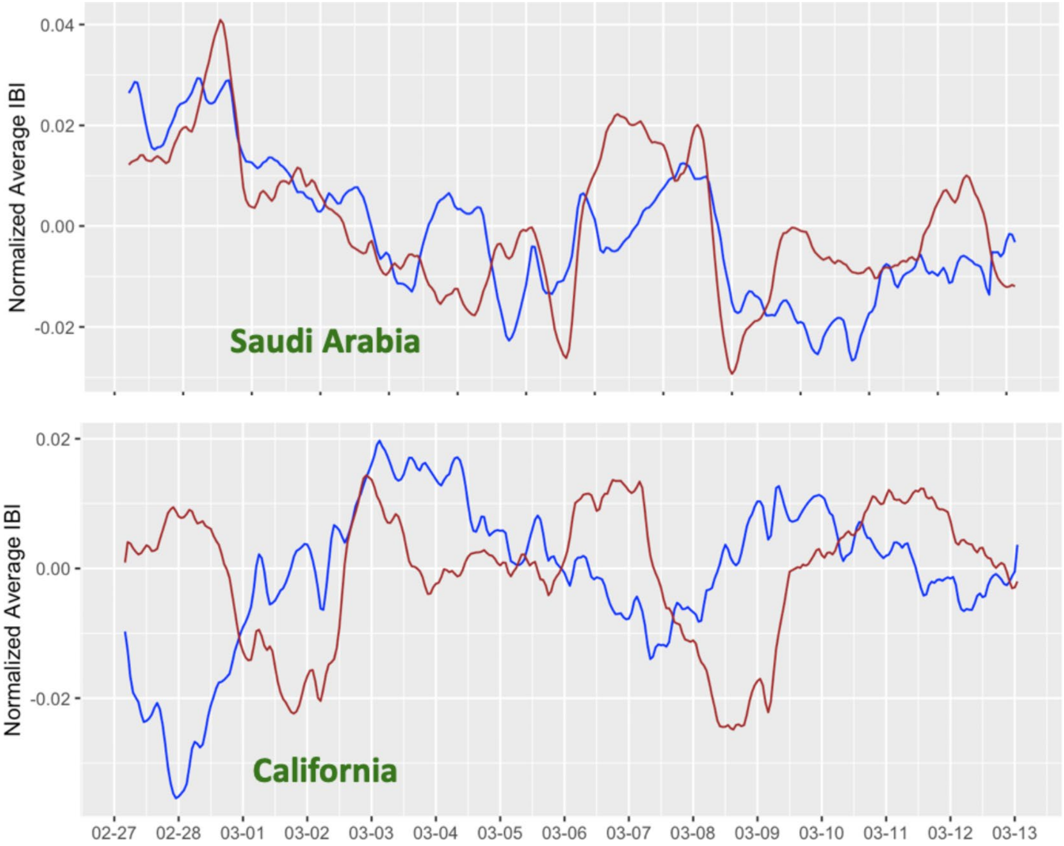

**Fig. 3**. Typical split half examples in two of the regions. In the top pane, when the Saudi Arabia group is split into two groups (blue and brown curves), the normalized average IBI of the groups are seen to be similar, with high correlation. In contrast, in the bottom pane, when the California group is split into two, the IBI's are seen to be different, with low correlation.

Interestingly, Saudi Arabia and New Zealand are also the only two geographic locations where a significant circaseptan component was detected across the participants within each region, using population-mean cosinor on all participant data (Table 1). Individually, a weekly variation characterizes close to 35% of the participants in New Zealand and 40% in Saudi Arabia, compared to 30% or less in the other countries. The tighter clustering of the phases of the circaseptan component in New Zealand and Saudi Arabia also contributes to the demonstration of a significant weekly variation on a population basis in these two countries.

A secondary analysis of the normalized average daily means was consistent with this and revealed more about it. For the group in Saudi Arabia, a single 7-day cosine model approximates these average relative daily rhythm-adjusted mean value (Midline Estimating Statistic of Rhythm, MESOR) with near significance ($P=0.063$), while a two-component model including the 3.5-day term reaches significance ($P=0.045$). The maxima of the models align with the peaks in the IBI centered on February 28 and March 7, 7 days apart (Fig. 1). This analysis was limited by excluding some days and participants from the data, but it corroborated the significant findings of the population-mean cosinor analysis.

Synchronization was also investigated in individuals between different regions, but no significant correlations were found. This method of analysis was similar to analyzing within the same region, except that one split half group was formed from half of the participants in one region and the other group was formed from half in another region. There were not common underlying trends across regions that were observable in this analysis (Table 2).

These results were corroborated by a similar analysis taking pair correlations for each pair of individuals and then averaging across all the pair correlations in a region. This method was tried across various heart rate metrics (see Table 3), in addition to IBI. This gave similar results in terms of p-value as in Table 1, even though the mean correlations were small. Conversely, the correlations in the split half analysis were much stronger and visible to the eye as in Fig. 3. The averaging across participants smooths out HRV noise of the individual, which allows group HRV patterns to be more apparent.

The results were also corroborated by a block shuffling analysis. This was performed over all pair correlations across all 5 regions, constraining the analysis only to pairs of participants in the same region as each other. Over all block sizes that we tried, the result was significant at $p<0.05$.

The results also seem to be robust to discontinuities between the endpoints that are stitched together by the cyclic permutation process. The cyclic rotation process can result in a large jump in the time series when

| Location | *N* | Age, y | | Gender, % female |
|---|---|---|---|---|
| | | Mean | SD | |
| United Kingdom | 14 | 39.2 | 12.3 | 57% |
| Lithuania | 20 | 23.3 | 0.6 | 80% |
| New Zealand | 22 | 42.7 | 10.1 | 50% |
| Saudi Arabia | 20 | 20.7 | 2.6 | 50% |
| United States | 20 | 54.7 | 8.4 | 55% |
| All participants | 96 | 36.0 | 15.1 | 58.33% |

**Table 2**. The age and gender breakdown for all participants by country.

| | HR | LnLF/HF | RRI | SDNN | LnTP | LnVLF | LnLF | LnHF | LnRMSSD |
|---|---|---|---|---|---|---|---|---|---|
| HR | **1** | **0.73** | 0.98 | − 0.69 | 0.62 | − 0.62 | 0.47 | 0.71 | − 0.79 |
| LnLF/HF | **0.73** | **1** | 0.68 | − 0.56 | 0.53 | − 0.5 | 0.33 | 0.78 | − 0.81 |
| RRI | 0.98 | − 0.68 | **1** | **0.72** | **0.64** | **0.65** | **0.48** | **0.68** | **0.74** |
| SDNN | 0.69 | − 0.56 | **0.72** | **1** | **0.96** | **0.96** | **0.84** | **0.85** | **0.79** |
| LnTP | 0.62 | − 0.53 | **0.64** | **0.96** | **1** | **0.98** | **0.91** | **0.89** | **0.83** |
| LnVLF | 0.62 | − 0.5 | **0.65** | **0.96** | **0.98** | **1** | **0.85** | **0.83** | **0.78** |
| LnLF | 0.47 | − 0.33 | **0.48** | **0.84** | **0.91** | **0.85** | **1** | **0.83** | **0.73** |
| LnHF | 0.71 | − 0.78 | **0.68** | **0.85** | **0.89** | **0.83** | **0.83** | **1** | **0.94** |
| LnRMSSD | 0.79 | − 0.81 | **0.74** | **0.79** | **0.83** | **0.78** | **0.73** | **0.94** | **1** |

**Table 3**. Correlations among different HRV metrics. There are 2 main correlating blocks shown in bold; metrics within a bold block tend to correlate strongly with each other, whereas metrics from different blocks tend to anti-correlate strongly.

the original endpoint is placed next to the start point. Robustness to this behavior was tested by rerunning the analysis with 24 time points surrounding the discontinuity being removed after the rotation. The resulting p-values for the correlations changed negligibly. This makes sense, since only 1 day out of a 2-week period was removed.

## Discussion

This is the first global dataset collected that measured synchronization at several locations across the globe continuously for multiple weeks. Also, aside from one 15-minute period, they were not instructed to perform any particular tasks together. Two very different approaches found similar behavior for just two of the groups, those in Saudi Arabia and New Zealand. Significant long-term cross correlations were observed across participants within the same region. These are also the only two geographic locations where a significant circaseptan component was detected by population-mean cosinor.

A natural question is why synchronization was only observed in some regions but not others, nor in participants across multiple regions. One hypothesis we propose is that participants in these groups were socially closer than those in the other groups, consistent with past studies[11,33,36,41]. In Saudi Arabia, the participants were tightly knit, shared some religious practices and student classes, and included several family units. In New Zealand, many participants were part of a community of living and studying together as part of the Embassy of Peace. Conversely, the California group included members spread across the region, the England group comprised business people and others that were not connected to each other, and the Lithuania group were college students that did not typically connect outside of classes or share living quarters.

A separate analysis also revealed only in Saudi Arabia and New Zealand a significant circaseptan component in the heart rhythms. In Saudi Arabia, this is visually evident in the Saturday peaks on 2/28 and 3/27 (Fig. 1). In New Zealand, the weekly routine is less evident but still significant. It may be that since they shared similar weekly routines or rhythms they experienced heart synchronization.

It is worth considering to what extent these shared weekly routines, or weekly or daily rhythms that are general to the population, contribute to the long-term correlations that were observed. It seems unlikely that these are patterns of the general population, as then they should have showed up across all of the regions, not just Saudi Arabia and New Zealand, even though they have such geographical and cultural differences. Also, all correlation analyses were performed after a 24-hour moving average to remove dominant circadian rhythms. However, there is evidence for weekly rhythms particular to these groups. The method of swapping weeks in the observed dataset to focus on weekly rhythms reduced the mean correlations from 0.52 to 0.27, but it resulted in a consistent positive distribution of the correlations. It appears that weekly rhythms partially contribute to correlations, in addition to long-term movements. It is visible (Fig. 1) that participants in these regions have some weekly recurrences but also important differences between the first and second week. For example, in

Saudi Arabia (Fig. 3) participants exhibit a recurring peak on Saturday, but they share a downward trend in the first week followed by an upward trend in the second week. Also note there were no special holidays or events in Saudi Arabia and New Zealand at this time. The weekly rhythms particular to these regions seem to partially account for the long-term correlations. Taken together with the long-term movements of HRV, the result is significant synchronization. This is consistent with the hypothesis of social closeness, with participants in these regions sharing long-term and weekly rhythms.

As an initial check on this hypothesis, the New Zealand group was further split into the North Island and South Island group, and the synchronization analysis was redone for these groups. The rationale was that it was only the 22 North Island participants that lived together in close social contact, but the 7 South Island participants were not connected to each other. It was indeed observed that the North Island group exhibited significant correlations, whereas the South Island group did not. This provides supporting evidence for this hypothesis. Further research is needed in future to include validated measures of social closeness as a dimension in the experimental design, but these initial findings are encouraging.

Another hypothesis that was considered was that the Earth's magnetic field was interacting with or mediating the HRV synchronization[42,43]. The HeartMath Institute makes continuous measurements of the magnetic field near most of the regions of interest. However, correlations between each region's average HRV and the local magnetic field were only significant in certain cases, which was not consistent with the locations where HRV synchronization was observed. In future, correlations between the HRV and other environmental variables such as local weather or space weather could be explored.

In future, it would be interesting to consider a lagged analysis, to see whether there were any correlations between participants that might engage in similar behavior in a consistent but asynchronous manner. It is further possible that although correlations were not found across participants in different regions at the same time, there may be lagged correlations corresponding to their time zone differences. This direction was not pursued here under the assumption that long-term correlations over 2 weeks would not change much by a lag of a few hours, but this could be further explored.

One potential objection to this study is that the correlations (e.g. in Table 1) are inflated since HRV signals are autocorrelated, especially when adding a 24-hour moving average smoothing. However, this was accounted for by using cyclic permutations to calculate p-values; the surrogate data was subject to the same inflation of correlation, since the autocorrelations were preserved and the same smoothing was applied. The observed correlations in Saudi Arabia and New Zealand were still significantly stronger than expected. Another objection may be to the use of minimum and maximum for normalization of the heart rhythm time series rather than the standard deviation that is more robust. However, use of min and max were preferred in this case since they allowed normalization between $-1$ and 1 and HRV data is not normally distributed. Either way, this choice was of minor consequence because outliers were removed, and the standard deviation was found to be closely related to the min/max for all participants.

## Conclusion

Synchronization among the heart rhythms of multiple participants has been observed in various contexts, but this is the first global dataset collected that simultaneously measured synchronization at several locations across the globe continuously for multiple weeks. Also unique is that, for the most part, they were not instructed to perform any particular tasks or activities together. Even so, cross correlations were observed across participants within the same region, for the groups in Saudi Arabia and New Zealand. This is a surprising result, given that each participant has an individualized life and distinct heart rate. Two very different approaches found similar behavior for just these two groups and not the other three. Synchronization was observed across participants within the same region, as long-term correlations. In addition, a significant circaseptan component was detected by population-mean cosinor. A hypothesis is proposed to explain this, that participants in these groups were socially closer than those in the other groups, sharing similar behaviors and practices, some of which were weekly routines. It would then appear that HRV among humans synchronizes simply due to social proximity, even when they are not physically near each other or performing tasks together.

The potential implications of this study are that simply being in close contact with each other, humans synchronize at the physiological level of their hearts. This may very well be an indicator for social coherence, which means it affects human health. It highlights the importance of caring for our own wellbeing and that of others. Prosocial behavior affects not only the psychological state of those around us, but our heart rhythms are shared as well. We may not know yet which components of our HRV are shared, but it seems that we are sharing with those around us over the long term. The horizon of discovery lies ahead to find out just how deeply humans can connect.

## Materials and methods

### Participants

During the 15-day period between 26 February and 13 March 2015, 104 participants located in California, USA, Lithuania, Saudi Arabia, New Zealand, and England participated in the study. All the participants were healthy and either worked or attended classes during daytime hours. The Lithuanian group consisted of 20 medical students attending the Lithuanian University of Health Sciences. Most of the participants knew each other, and the relationships among them were reported as generally good and as casual acquaintances. The California group consisted of 20 individuals, some of whom were employees at the HeartMath Institute (HMI) in Boulder Creek, California and worked in separate offices at two different locations. The other participants were acquaintances who lived in various locations in California. Although there were some close social relationships reported in the group, the majority were either casual acquaintances, and many did not know each other. The New Zealand group consisted of 29 individuals, 22 of whom were located together on the North Island while 7 lived in different locations on the South Island. Among the North Island group, eleven of these were staff members of Freedom Farms who founded an organization called The Embassy of Peace, while the other eleven were participants living at the center. The center is a place where people from different backgrounds gather to experience community and family peaceful living in harmony with the land. Its mission is to provide a space that models peaceful living. All of the North Island group members were reported to have longstanding and meaningful relationships with each other and performed daily activities together. The Saudi Arabia group of 20 participants primarily consisted of medical students attending the college of medicine at the King Faisal University and included several family units. The male and female group members often met and prayed together in separate groups and were reported to be a tight knit group with strong emotional bonds amongst most of the group members. The group located in England consisted of 7 business leaders and 7 acquaintances of the study coordinator, and they were located in various UK locations. This group was reported to have low social interactions and many of the group members did not know each other.

Each location had a local site coordinator who was responsible for participant recruitment, logistics coordination and participant training in the study procedures and use of the HRV recorders. Study coordinators in the 5 countries recruited a total of 104 participants, selected by convenience. One participant failed to return their HRV recorder at the end of the study and 7 were excluded from the long-term correlation analysis due to missing data. Thus, the number of participants dropped to 96 at the end of the study. The mean age (SD) of the 96 participants in the analysis was 36 (15.1) years, consisting of 56 females and 40 males. Table 2 contains the age and gender breakdown for all participants by country.

The local study coordinator in each country excluded candidates that had any of the following conditions; heart disease of any type, heart irregularities (arrhythmia, fibrillation etc.), hypertension, diabetes, severe anxiety or depression that requires prescription medication, and conditions like sleep apnea requiring the use of a CPAP. The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Kaunas Regional Ethics Committee for Biomedical Investigations (No. BE-2-51, 23 December 2015). Informed consent was obtained from all subjects involved in the study.

## HRV data collection

HRV is a non-invasive measure that reveals the dynamic activity of individual's ANS[44]. The participants all had 24-hour ambulatory HRV recordings recorded daily over a two-week period from 26 February to 12 March 2015. Each participant was instructed on how to attach, start, and stop the recorders at the start of the study (Bodyguard2, Firstbeat Technologies Ltd., Jyväskylä, Finland) by the site coordinator, who retrieved the data from the HRV recorders and uploaded them to the FTP data collection site.

Participants were instructed to notate daily activities such as sleep and waking times, etc. They were shown how to pause the HRV recorder when needed and had up to one hour to bathe, etc. before restarting the recorder. Ambu Blue Sensor L microporous disposable electrodes were placed in a modified V5 position. To reduce skin irritation, participants were advised to position the electrodes at three distinct locations near the V5 position. The inter beat-interval (IBI) was computed by the HRV recorder using the electrocardiogram at a sample rate of 1000 Hz. The recorded RR intervals were stored in the HRV recorder's memory and subsequently uploaded to the study FTP site upon completion of the study. Subsequently, the HRV data were retrieved and subjected to analysis using DADiSP 6.7. IBIs that were either less than or greater than 30% of the mean of the previous four intervals were excluded from the analysis dataset. Following an automated editing procedure, an experienced technician manually reviewed all recordings and made corrections as necessary. To adhere to the standards set by the International HRV Task Force, all HRV recordings were segmented into consecutive 5-minute segments[45]. Any 5-min segment with $>10\%$ of the IBIs either removed or missing were excluded from the analysis. The local time stamps in the HRV recordings were converted to Coordinated Universal Time (UTC) to ensure synchronization between participants in different locations.

Out of the initially scheduled 32,256 h of recording (96 participants × 14 days × 24 h), a total of 95% (30,621 h.) remained available after factoring in missed recordings, data clearing, and editing. Merely 7 participants fell below 80% of the initially planned recording hours, with only two of them recording less than 70%.

## Computation of HRV synchronization

To compare multiple participants, each participant's IBI over time was first normalized by subtracting its mean and dividing by the maximum of its absolute value over the 14-day period to ensure a range between $-1$ and 1. Then, 24-hour smoothing was applied via a simple moving average to mitigate trivial correlations among participants due to shared circadian rhythms. The average of this processed data across all participants for each region is shown in Fig. 1.

IBI is the basic HRV measure, and we did also consider other typical measures, including heart rate (HR), standard deviation of IBI (SDNN), and natural logs (ln) of root mean squared standard deviation (RMSSD), high frequency power (HF), low frequency power (LF), very low frequency power (VLF), total power (TP), and the ratio of LF/HF. However, even after normalization and smoothing, they strongly correlate or anti-correlate with each other over the 14-day period, as shown in Table 3. Therefore, the results in this paper were found to be qualitatively similar regardless of which metric was chosen.

In terms of missing data, most participants were missing very few or no data points, and those missing points could be filled in with the moving average smoothing. However, 13 participants (6 of them in England) were missing large chunks of 12 or more hours of data in the middle of the time period, which would impact smoothing and correlations. These participants were removed from the analysis. Some analyses were checked with and without the missing participants, and removing them did not seem to qualitatively affect the results. However, it was deemed prudent to remove them.

Synchronization was measured as long-term correlations among participants' heart rates (inter-beat intervals). To calculate correlations among participants, a split-half analysis was performed within each region. The participants in that region were randomly split into two equally sized groups (or groups only one off in size for an odd number of participants), and the mean IBI over time of each group was calculated on the smoothed IBIs. Then, the Pearson correlation between the two group time series was computed. These steps were repeated 1000 times for different choices of random split for the two groups, and some examples of resulting time series and correlations are shown in Fig. 4. Finally, the mean of these correlations was extracted as the regional mean correlation.

The statistical significance of correlations was determined with surrogate data by shuffling the HRV data, with a cyclic rotation analysis[46–48]. HRV metrics - like most biological metrics - are autocorrelated because they are continuous over time. This is especially true after a 24-hour moving average, which connects each time point to the 24 h surrounding it. Thus, the correlations of the observed HRV data should be compared to permutations that are similarly auto-correlated. This is achieved by cycling the HRV of a given participant to maintain the time ordering of the HRV values. In other words, one time point $t_0$ in the data is chosen at random, and the values

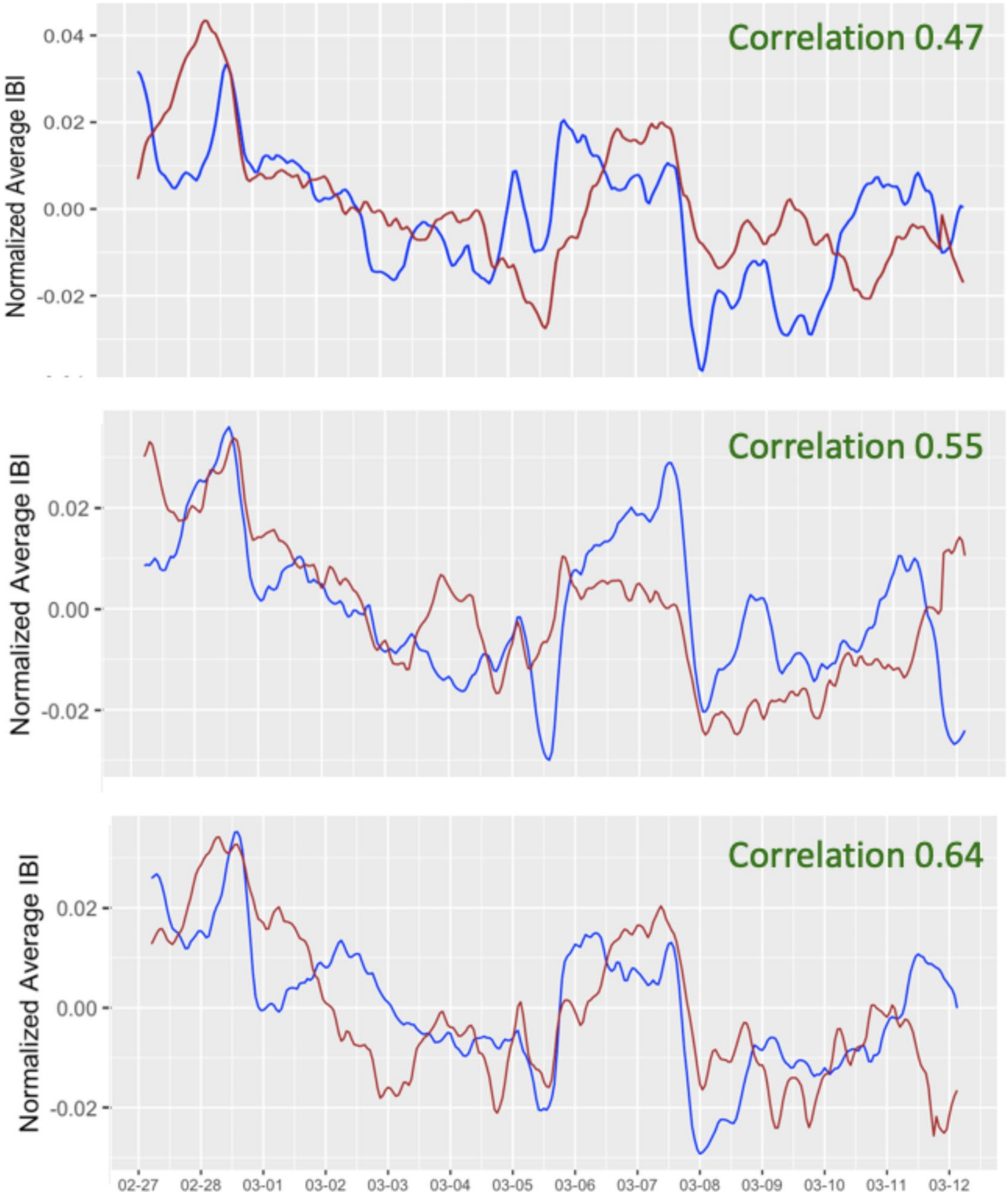

**Fig. 4**. Sample split-half time series for the participants in Saudi Arabia. In each pane is shown the time series of the two groups after averaging across its participants, and the Pearson correlation between them. A different random selection of grouping was chosen in each of these three runs, a subset of 1000 total runs performed per region.

are translated to the right until $t_0$ is at the end of time range, with any values that are translated past the end of the time range being cycled around to the beginning of the time range. Another way to put it is that the values to either side of $t_0$ are swapped in position. An example is shown in Fig. 5.

To scale this split-half and cyclic rotation analysis to all participants in a given region, the normalized HRV of all participants was randomly cyclically rotated and then smoothed with a 24-hour moving average to produce a surrogate ensemble. Correlations were calculated for 100 iterations of split-half configurations, and a mean correlation was extracted. This whole process was iterated on 1000 surrogate ensembles to produce a distribution of expected regional mean correlations from which to calculate p-values. One-tailed p-values were used, since we only hypothesize positive correlations in a split-half analysis where we propose there is synchronization.

Another similar analysis was performed to corroborate the regional mean correlation analysis. The above analysis is a correlation of mean HRV time series, but an alternative is taking pair correlations for each pair of individuals and then averaging across all the pair correlations in a region. Significance was again measured via cyclic rotation analysis.

Another corroboration performed was to employ another shuffling strategy, a block shuffling analysis. The steps were essentially the same, but instead of cyclic rotation, the data were split into equal-sized blocks and then those blocks were randomly shuffled. This is not as effective at preserving the autocorrelation, but it makes for surrogate data that is more clearly different from the source data being permuted. The analysis was repeated for various block sizes, up to the limit of splitting the time series into just 2 blocks, which recovers the cyclic rotation result.

## Spectral analysis of IBI and assessment of circaseptan component

Hourly averages computed from the 5-minute segments of R-R intervals from normal-to-normal beats served for least squares spectral analysis[49]. The method, based on the cosinor, is applicable to non-equidistant data, thus allowing the analysis of data series from all 103 participants that returned their recorders. Individual spectra spanned a frequency range extending from one cycle per 7 days to one cycle per 3 h, yielding estimates of amplitude and phase at each trial frequency (or period = 1/frequency), in addition to the overall rhythm-adjusted mean value (Midline Estimating Statistic of Rhythm, MESOR). All data series used a reference time of 25 February 2015 00:00 UTC. Population spectra, obtained by averaging amplitudes at each trial frequency across participants, identified spectral peaks corresponding to periodic signals. Population-mean cosinor spectra[49] obtained as vectorial averages of (amplitude, phase) pairs at each trial frequency across participants in each geographic location further checked whether signals detected were synchronized in phase among individuals. Rejection of the zero-amplitude (no-rhythm) hypothesis of anticipated periodic components such as the about 7-day (circaseptan) and about 24-hour (circadian) components and their harmonic terms indicates that a periodic signal is detected with statistical significance. Statistical testing was set at a probability of 5% ($p < 0.05$).

Additionally, models of the circaseptan rhythm were fit to normalized average daily means. Estimates were obtained of the MESOR of a 24-hour cosine curve fitted to each day separately for days with at least 18 h of data. Models of the circaseptan rhythm are fitted to the relative daily MESORs averaged across those participants with more than 10 days of daily MESORs available over 15 days. This analysis was limited by excluding some days

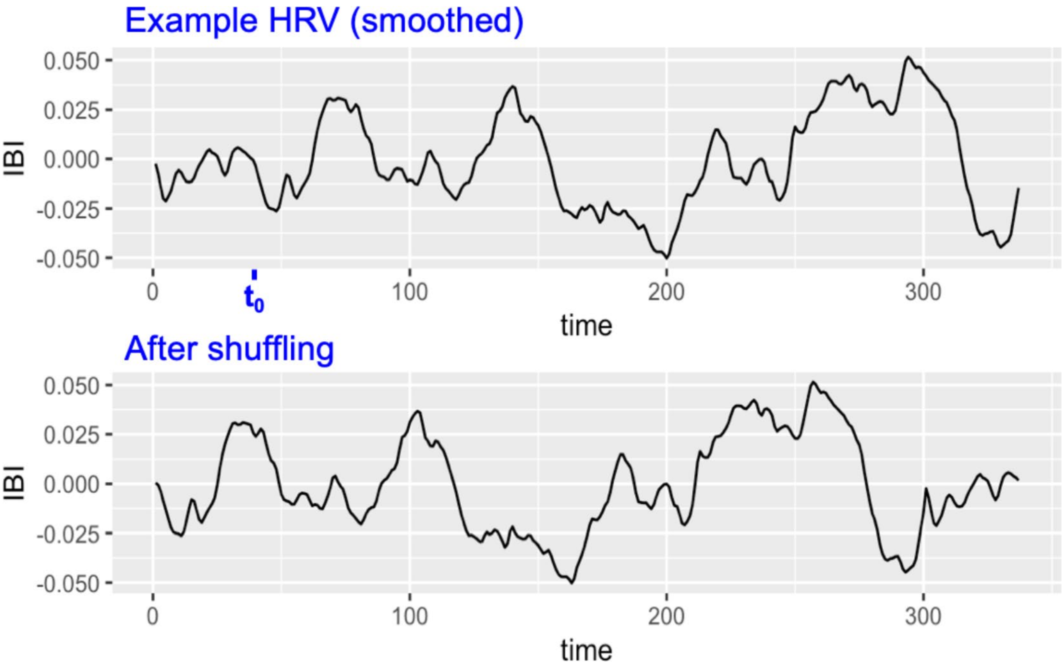

**Fig. 5**. Example IBI time series. Top pane: Original normalized smoothed values. Bottom pane: Shifted values after cyclic rotation using randomly chosen $t_0$.

and participants from the data, so it was intended as a corroboration and visualization of the population-mean cosinor analysis.

## Data availability

All datasets analyzed in the current study are available from the corresponding author on reasonable request.

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## Author contributions

N.P., design of study, HRV synchronization analysis, statistical analysis, writing; M.A., organization of data collection, integration, and cleaning; R.M., writing Introduction, coordinating global data collection; G.C., cosinor analysis and writeup; A.C.T., cosinor analysis and writeup; M.R., review; A.V., review.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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