Synchronized arousal between performers and related spectators in a fire-walking ritual

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Collective rituals are present in all known societies, but their function is a matter of long-standing debates. Field observations suggest that they may enhance social cohesion and that their effects are not limited to those actively performing but affect the audience as well. Here we show physiological effects of synchronized arousal in a Spanish fire-walking ritual, between active participants and related spectators, but not participants and other members of the audience. We assessed arousal by heart rate dynamics and applied nonlinear mathematical analysis to heart rate data obtained from 38 participants. We compared synchronized arousal between fire-walkers and spectators. For this comparison, we used recurrence quantification analysis on individual data and cross-recurrence quantification analysis on pairs of participants' data. These methods identified fine-grained commonalities of arousal during the 30-min ritual between fire-walkers and related spectators but not unrelated spectators. This indicates that the mediating mechanism may be informational, because participants and related observers had very different bodily behavior. This study demonstrates that a collective ritual may evoke synchronized arousal over time between active participants and bystanders. It links field observations to a physiological basis and offers a unique approach for the quantification of social effects on human physiology during real-world interactions.

social interaction | mirroring | recurrence plots | collective effervescence | social anthropology

Collective ritual action is a ubiquitous aspect of all known human cultures. Social scientists have long theorized about its origins and possible functions. Anthropologists have observed that collective rituals foster social assimilation (1), enhance prosociality (2, 3), and reinforce social solidarity and group cohesion (4–6). Thus, rituals may become vehicles for social organization and transformation by contributing to the formation of strong emotional bonds between group members (7, 8).

Previous research has investigated the relationship between synchronous activity and social rapport (9–11). Marching in step, chanting, dancing, playing music in unison, and other synchronous ritualistic activities are found in all cultures (12). Previous studies have shown that synchronized behaviors enhance cooperation within groups (13, 14) and lead to increased rapport between group members (15, 16). Thus, the suggestion is made that rituals involving synchronous actions are adaptive in promoting social cooperative behavior (14).

However, the question remains whether it is the matching of actions performed that leads to increased rapport (17), or shared emotion that results from taking part in the same event (4). For example, the former mechanism would fail to describe the social effects of those collective rituals from which synchronized actions are absent.

One well-known theory comes from Émile Durkheim, who attributed these effects to the notion of "collective effervescence", arguing that:

> The very fact of congregating is an exceptionally powerful stimulant. Once the individuals are gathered together, a sort of electricity is generated from their closeness and that quickly launches them to an extraordinary height of exaltation... Probably because a collective emotion cannot be expressed collectively without some order that permits harmony and unison of movement, these gestures and cries tend to fall into rhythm and regularity. (4)

Although this idea of a "collective effervescence" is purely theoretical, it could be translated into different terms, perhaps via a more concrete biological mechanism. We hypothesized that one such mechanism could be synchronous arousal, which may be related to empathy and affective mirroring (18, 19).

With this hypothesis in mind, we assumed that such synchronous arousal would be detectable in physiological states of ritual participants. To test this experimentally, we measured heart rates during the course of a fire-walking ritual. We equated arousal with fluctuations in the autonomic nervous system and concomitant heart rate activity.

The ritual investigated in this study was chosen because it is highly arousing and does not involve overt behavior synchronized in time. This enabled us to investigate synchronized arousal instead of synchronized body movements, measured as heart rate data from active participants and spectators of the ritual. The study was conducted in San Pedro Manrique, a rural Spanish village of 600 inhabitants, during the annual fire-walking ritual. The ritual is performed at midnight on the 23rd of June at the height of the summer solstice (20). It takes place in a specially built amphitheater, which can accommodate up to 3,000 spectators.

The fire consumes more than 2 tons of oak wood and burns for 4 h before it is reduced to a carpet of glowing red coals. Once the coal bed is ready, the fire-walkers begin their procession, accompanied by music and a large crowd, parading through the Town Hall Square before they enter a cleared space at the focus of the amphitheater. The amphitheater is packed with spectators, including local inhabitants and visitors from out of town.

After dancing for several minutes in a circle around the glowing bed of coals, the fire-walkers assemble and decide the order in which they will cross. They then take their place on the ground to wait their turns. The sound of a trumpet beckons each fire-walker to the walk, one by one. The fire-walk is conducted bare-footed, and most walkers carry another person on their backs while crossing the fire, typically a spouse, relative, or

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friend (Movie S1). Once they have crossed over, their closest friends or relatives rush over to hug and congratulate them.

According to our hypothesis, synchronized arousal is one mechanism that ties the ritual participants together—not just performers, but observers as well. We thus expected to find shared arousal between fire-walkers and spectators, even though the spectators did not perform the same actions but merely witnessed the ritual. Previous research has investigated physiological responses among spectators to televised sporting events (21), showing joint elevation in heart rate when their teams scored a goal, as well as effects of sporting events on cardiovascular mortality (see ref. 22 for review). Here, however, we quantify levels of coupling of physiological states between participants and spectators.

Much research has investigated the capacity of people to feel what others are feeling, through action observation and mirroring (23), particularly as concerning pain empathy (24). Research in neuroscience suggests that highly similar patterns of brain activity are present in an observer as in the observed actor who has the first-hand experience of the emotion (25). According to these findings, we might expect synchrony between fire-walkers and any of the spectators. However, empathy and communication of emotion entail other factors as well, such as the context and the intensity of the observed emotion (26), which could also be modulated by the relationship between the observer and the actor (27).

These considerations suggest that we may find more synchrony in arousal between fire-walkers and closely related spectators compared with fire-walkers and unrelated spectators. To address this, we investigated the effects of the ritual on the group, of different degrees of relatedness. Finding a relationship between "relatedness" of fire-walkers and spectators and synchronized arousal would indicate socially mediated effects on physiology during collective actions. To test for synchronized arousal, we measured heart rates of three different groups: (*i*) fire-walkers, (*ii*) local spectators who were friends or relatives of the fire-walkers, and (*iii*) nonrelated, nonlocal spectators.

Results

Twenty-eight participants crossed the carpet of glowing red coals, 7 m long, with surface temperatures of 677 °C. Continuous heart rate data were recorded from three groups of participants: (*i*) 12 fire-walkers, (*ii*) nine spectators who were either relatives or friends of at least one fire-walker, and (*iii*) 17 spectators, not related to any of the locals, who were visiting the village for the ritual. Each participant wore a transmission belt around their chest, which recorded heart rate averaged over 5-s intervals. Each walk lasted 4 to 5 s, corresponding to a single data point.

We report data from two source epochs: a 30-min baseline, recorded 2 to 3 h before the ritual, and the 30 min that spanned all 28 individual fire-walks. Analyses were conducted using all of the data points from the baseline and ritual epochs. These two epochs were analyzed separately. Raw pulse data revealed striking qualitative similarities during the ritual between the heart rates of fire-walkers and heart rates of relatives and friends, with no apparent similarity to nonrelated spectators (Fig. 1*A*).

To quantify intra- and interpersonal effects of the fire-walking ritual, we performed recurrence quantification analysis (RQA) on individual data, and cross-recurrence quantification analysis (CRQA) on paired participants' data. These methods were chosen over correlation analysis because the latter treats data

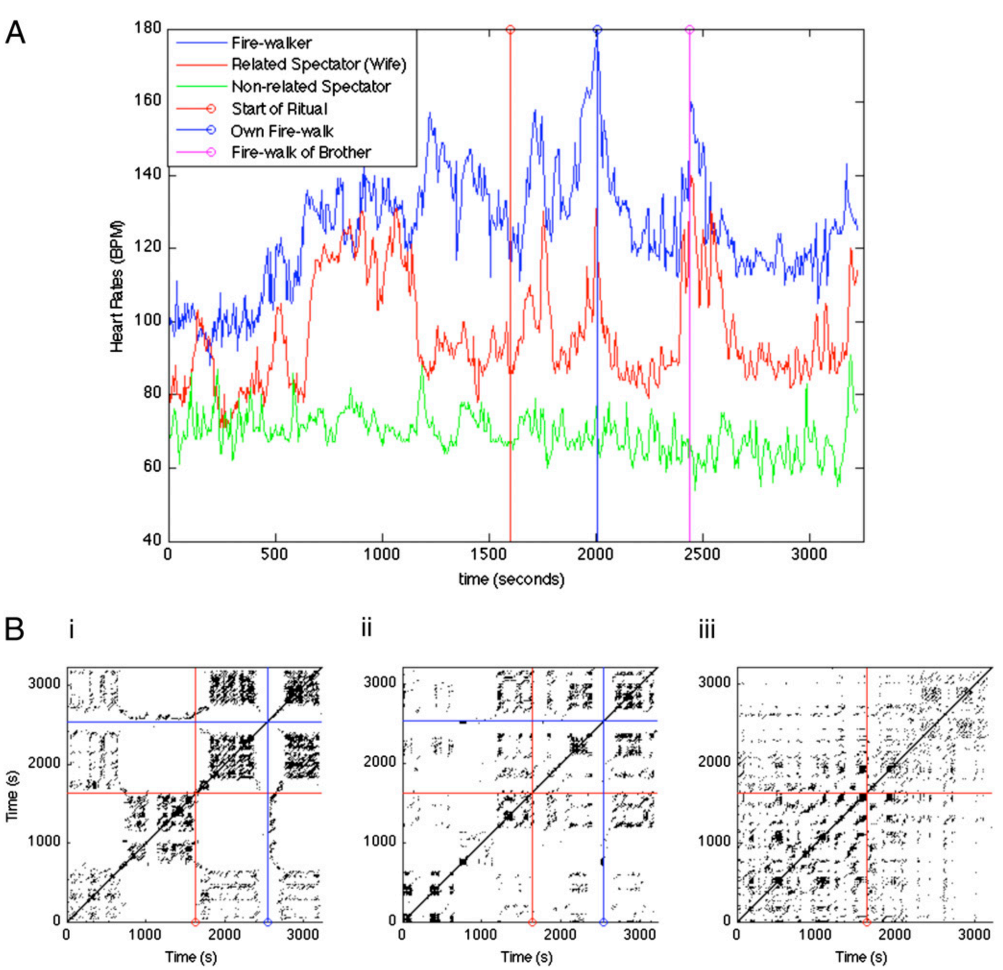

Fig. 1. (*A*) Heart rates (beats per minute) recorded during the procession and the ritual from a representative fire-walker (blue), related spouse-spectator (red), and unrelated spectator (green). The red, blue, and pink lines mark the beginning of the ritual and the times this fire-walker and his brother cross the fire, respectively. (*B*) Recurrence plots for a (*i*) fire-walker, (*ii*) related spectator, and (*iii*) unrelated spectator just before the ritual and during the ritual at 2% recurrence rate. The red and blue lines mark the beginning of ritual and the time of shown fire-walker's walk, respectively. The *x* and *y* axes of the recurrence plots are the time axes of the shown participant's heart rate. Note: The epoch shown before the ritual was part of the procession and thus not used as the baseline.

series as stationary, which they are not. Correlations use averaging to determine similarity between signals along an entire epoch, ignoring changes that take place throughout. RQA and CRQA, on the other hand, are nonlinear methods that allow quantification of dynamical systems and their trajectories. With these methods we are able to capture many properties of the heart rate dynamics that would otherwise be lost due to averaging with more traditional correlation analysis.

To quantify intrapersonal similarity, we first produced recurrence plots for each individual data set. A recurrence plot is a 2D plot, with the same participant's heart rate data series along each of its two axes (more detail is given in *Materials and Methods*) (28). Fig. 1*B* illustrates three recurrence plots produced from three individuals' data: a fire-walker, a related spectator (i.e., his wife), and an unrelated spectator. The global similarities between the recurrence plots of the fire-walker and his wife are visible by eye, as are global differences that distinguish the unrelated spectator's recurrence plot (i.e., in the latter case, a more graded diffusion of points throughout more regions of the plot).

Overall, the recurrence plots of all participants revealed interpretable differences in the patterns of organization around the ritual as a whole and the individual fire-walks, consistent with the illustrations shown in Fig. 1*B*. These "large-scale patterns" are referred to as the typology of the recurrence plot (28, 29). They can be either homogenous, periodic, drift, or disrupted (28). Recurrence plots allow for visualization and classification of such typologies. For fire-walkers and related spectators, the recurrence plots resembled a disrupted typology, with abrupt changes in the dynamics at the start of the ritual and the individual fire-walk. Fig. 1*B* shows the transition in dynamics from the procession to the ritual epoch. The procession was not included in the quantification of recurrence plots because we used a more neutral baseline instead (recorded hours before the ritual), as previously mentioned.

Interestingly, despite the superficially shared experiences of the related and nonrelated spectators—neither performed in the ritual, and both were seated throughout—the nonrelated spectators did not show these patterns. Instead, recurrence plots of their heart rates resembled a drift typology, with a pattern that fades in the upper left and lower right corners, caused by systems with slowly varying parameters (28).

To further analyze the similarity of participants' heart rates quantitatively, we performed RQA (30). RQA is a nonlinear mathematical tool used to quantify the number and duration of dynamical system recurrences from the recurrence plots, producing several metrics with which to estimate the similarity between different dynamical patterns. The metrics used to evaluate the heart rate data series estimate predictability (% DETerminism), stability (MAXLine), complexity (Entropy), and smoothness (Laminarity) of a data series (*Materials and Methods*). The four metrics were computed from the recurrence plots of the heart rate data for each participant and compared using a 3×2 mixed-model multivariate analysis of variance (MANOVA), with the group as a between-subjects variable and the source epoch (ritual vs. baseline) as the within-subjects variable (see Table S1 for significance values). The analysis yielded a statistically reliable main effect of the group [$F(8,64) = 2.75$, $P < 0.011$] across all four parameters and a significant interaction [$F(8,64) = 3.869$, $P < 0.001$] for three measures (although not entropy) but only a marginal effect of the source epoch ($P = 0.077$).

Post hoc tests using Bonferroni correction revealed a reliable difference between the fire-walkers and nonrelated spectators across all four of the similarity metrics; however, the same analyses failed to distinguish fire-walkers from related spectators, except in stability (MAXLine). Means and SEs for the four metrics are shown in Fig. S1.

To better understand this ritual–group interaction, we next examined more closely the similarity between heart rates of paired participants of different degrees of relatedness. To quantify interpersonal similarity, we computed CRQA on pairs of participants' data. CRQA is a nonlinear method for analyzing shared dynamics between two different data series (31). It is analogous to RQA, except one participant's heart data supply the *x* axis, and the other participant's data supply the *y* axis for the cross-recurrence plot. We used CRQA to evaluate the coupling between participants' heart rates with respect to the four metrics previously used.

Cross-recurrence plots were computed for three different pairs of participants: (*i*) related fire-walkers and spectators, (*ii*) tangentially related fire-walkers and spectators, whereby the spectators were related to one of the other walkers, and (*iii*) unrelated fire-walkers and spectators, whereby the spectators had no relation to anyone in the ritual. This allowed us to investigate how the ritual affected the group level and whether shared arousal was modulated by the level of relation.

The cross-recurrence plots showed recurrent dynamics distributed densely around the ritual and the individual fire-walk between the related walker–spectator pairs (Fig. 2*A*). A similar pattern of recurrent dynamics was also found when the spectator was related to someone else; however, for the spectator it corresponded to the time around the fire-walk of their relative (Fig. 2*B*). These patterns were much less apparent between the nonrelated fire-walkers and spectators (Fig. 2*C*), and the transitions were not visible for the nonrelated spectators' time series.

The four aforementioned metrics were compared using a 3×2 mixed-model MANOVA, with "relatedness" as a between-subjects variable, and the source epoch (ritual vs. baseline) as a within-subjects variable (Table S2). The MANOVA yielded a main effect of relatedness across all four metrics [$F(8,24) = 3.508$, $P < 0.008$], as well as a main effect of the ritual [$F(4,12) = 9.473$, $P < 0.001$], but only a marginal interaction, $P = 0.079$. The means and SEs of the four metrics for each "relatedness" pairing are shown in Fig. 3.

The paired synchrony of heart rates, comparing related vs. tangentially related pairs of participants, was not reliably different, as tested using the post hoc Bonferroni correction. The post hoc analyses also demonstrated that the heart rates of the

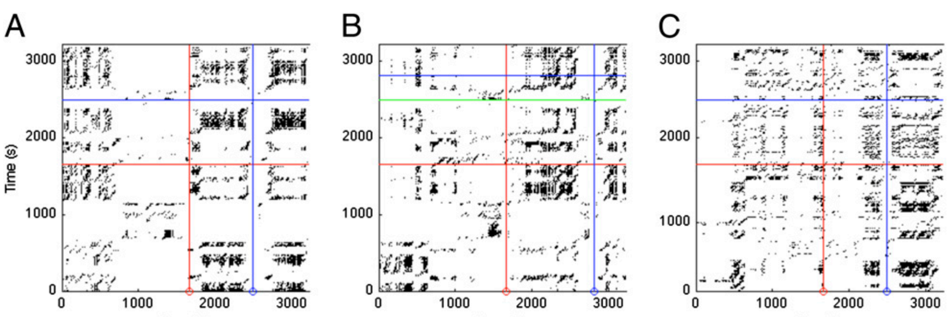

Fig. 2. Cross-recurrence plots of a (*A*) fire-walker and related spectator, (*B*) fire-walker and tangentially related spectator, and (*C*) fire-walker and unrelated spectator, at 2% recurrence rate, with the fire-walkers' time series along the *x* axis and the spectators' along the *y* axis. The red and blue lines mark the beginning of ritual and the time of shown fire-walker's walk, respectively. The green line marks the time of the related fire-walker's walk.

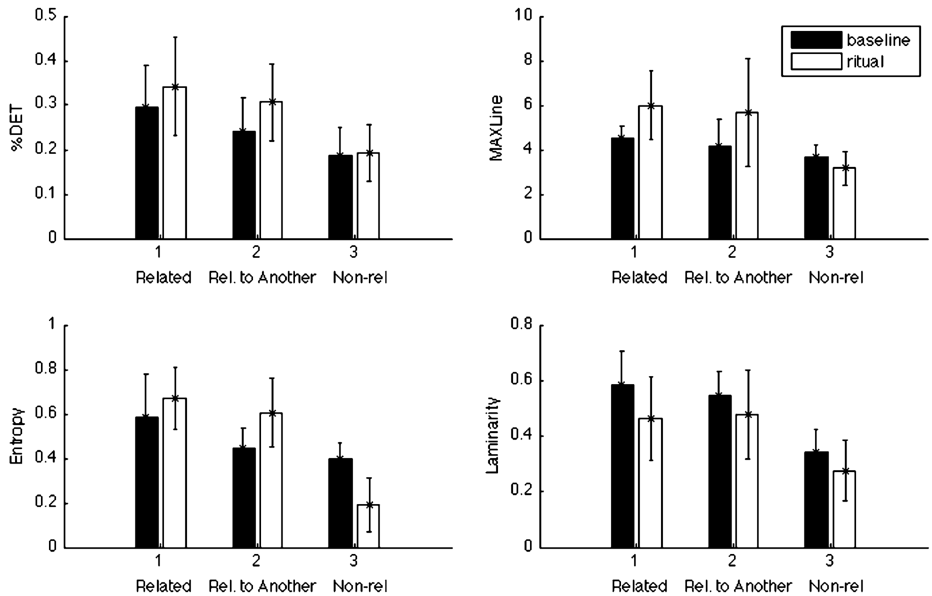

Fig. 3. Average CRQA metrics (%DET, MAXLine, Entropy, and Laminarity) during baseline (black) and ritual (white), across three different groups of paired participants: 1, fire-walkers and related spectators; 2, fire-walkers and tangentially related spectators; and 3, fire-walkers and unrelated spectators.

related and the tangentially related participants share more synchrony of dynamical structure than the pairs of unrelated participants. It is also noteworthy that the main effect of the source epoch, together with a marginal interaction, suggests that a reliable degree of synchrony is present between related pairs at baseline, which is amplified in the ritual epoch. This result mirrors the behavioral studies that find automatic entrainment between individuals engaged in shared activities (32–34).

Discussion

Many social theorists have speculated about the effects of collective rituals. It has often been proposed that synchronized action in rituals enhances group cohesion, which promotes cooperation between group members. Recent experimental studies have loosely supported this hypothesis by showing that interpersonal synchronized motor activity leads to increased rapport between people and prosocial behavior. We hypothesized that synchronized arousal even in the absence of synchronized action might be one mechanism responsible for these social effects of collective rituals. These effects have never been quantitatively investigated in a natural setting. The present findings show synchrony over time of bodily arousal between active participants with their related onlookers, a social modulation that is amplified in the ritual itself.

A qualitative look at the data showed that the fire-walkers' heart rates had a distinctive "signature," as seen across all 12 fire-walkers, with a high peak distributed around the walk itself (Fig. S2). The same pattern was seen with related spectators, whose heart rates peaked for the walk of their relatives and friends (Fig. 1*A*). To quantify this, we performed RQA on the data of each participant. Recurrence plots revealed characteristic patterns of organization, resembling a disrupted typology, around the ritual and the individual fire-walk for the fire-walkers and related spectators, but not unrelated observers (Fig. 1*B*). The unrelated spectators showed a drift typology with slow varying parameters and no visible transitions around the ritual or fire-walks.

The four RQA metrics obtained from the recurrence plots (%DET, MAXLine, Entropy, and Laminarity) were compared using a 3 × 2 mixed-model MANOVA, with the group as a between-subjects variable and the source epoch (ritual vs. baseline) as the within-subjects variable. The statistics revealed no significant difference between the fire-walkers and related spectators, except in stability (MAXLine). However, the heart rates of the fire-walkers were significantly more structured than those of the nonrelated spectators. The means of RQA metrics and the significant ritual–group interaction suggest that the heart rates of the fire-walkers were more structured during the ritual compared with the baseline, whereas the ritual had either the opposite effect or no effect at all on the nonrelated spectators.

Additionally, the individual fire-walking events had a structuring effect on the performers and their relatives, as shown by the recurrence plots. However, the statistics were not sufficient to capture the organizing effect of the fire-walks, because one sampled data point represented the entire span of time from the beginning to the end of a single fire-walk.

Therefore, the ritual as a whole affects the group differently depending on their involvement in it. To quantify shared dynamics between the groups, we performed CRQA on the three different groups of pairs, of varying degrees of "relatedness." The results confirm that related pairs had more "shared dynamics" between their heart rates than the nonrelated pairs. However, there was no statistically reliable difference between related and nonrelated walker–spectator pairs when the spectator was related to someone else in the ritual. Additionally, there was an increase in shared dynamics between fire-walkers and spectators during the ritual itself compared with baseline.

These shared dynamics do not merely refer to a common increase in arousal but rather to fine-grained commonalities of arousal patterns across the entire ritual. What these measures show then is not just that the heart rates go up at the time of the fire-walk, but that there are shared patterns of arousal that span the fire-walking ritual across all of the individual fire-walks, between performers and spectators that are related or tangentially related.

It would also be interesting to know whether these shared cardiac effects were predominantly sympathetic or respiratory-vagus mediated, by investigating the heart rate variability frequency bands. This is relevant, for example, to the question of whether breath holding or recitation of mantric prayers were related to the effect, as investigated in previous research (35). Although our data are not sufficiently fine-grained to assess potential interactions between levels of involvement and rates of breathing, it would be unlikely that the modulation of breathing rates alone would lead to coupling between participants and related spectators. This is because the breathing was spontaneous throughout the ritual, and the fire-walkers and spectators had different bodily behavior.

Other possible confounds to consider in this study are age, sex, and body mass index, which could have an effect on autonomic tone and reactivity. As in any ecological study, the environmental and behavioral confounds could have an effect on the experimental measures. However, the effects of these confounds were controlled through the use of our baseline measures.

These results suggest that the collective ritual experience is mediated by familiarity, because synchronized arousal is restricted to the ritual participants (i.e., fire-walkers) and their friends and relatives. Sharing of emotions merely through mirroring is of course possible and expected in the other spectators as well. It is, however, not enough to merely observe the ritual to show collective emotions experienced by the performers and their supporters. The observers must share membership in the group and have a relationship with at least one of the participants to share this tightly coupled group experience reflected in the heart rate dynamics.

The shared arousal hypothesis therefore seems consistent with the theory that rituals promote group solidarity. This "group" would not only consist of performers but also the observers that are their friends and relatives. Even though this shared arousal may not be found on each individual fire-walk, it is found across the time-span of the ritual.

It remains unclear whether shared arousal is the mechanism driving this collective experience or an emergent property of the ritual. Results do suggest that the heart rates of related walker–spectator pairs had more shared dynamics during the baseline as well, compared with the nonrelated pairs. One explanation for this could be that the anticipation of the ritual carries structure as well, for those who are related compared with the rest, because the baseline was measured only a few hours before the ritual. It could also be that relatedness plays a role in structuring people's heart rates with those close to them. However, this remains to be investigated.

Not surprisingly, this highly arousing ritual affects the physiological states of both participants and spectators, which can be seen both intra- and interpersonally. However, coupling of arousal patterns occurs between fire-walkers and related spectators only, as indexed by heart rate, with the ritual as the structuring event. The lack of physical contact between fire-walkers and related spectators suggests that the coupling between them must have an informational basis (36, 37). The synchrony of the physiological markers shared by the two beings cannot be due to direct exchange of matter or energy, leaving only the information available to spectators and participants as the basis of the coupling. Whether information is sufficiently salient to bring about coupling is determined by whether the spectator is related to at least one of the fire-walkers; hence, the coupling is socially modulated. The shared dynamics of heart rate are thus the consequence of socially modulated information-mediated coupling. This investigation opens a new dimension on the study of social relations and rituals, allowing the quantification of social effects in human physiology.

Materials and Methods

Participants. Participants were recruited from the Spanish village, San Pedro Manrique. Out of 28 people who walked across the fire, heart rates were measured from 12 volunteers (11 male, mean age 32.5 y, range 19–46 y). Additionally, measurements were collected from 26 spectators (16 male), of which nine were either relatives or self-reported friends of at least one of the fire-walkers (five male, matched for age ± 5 y), recruited through the fire-walkers. The rest of the spectators (11 male, matched for age ± 5 y) were not related to any of the fire-walkers and were recruited at random, hours before the ritual began. All of the participants gave written, informed consent before participation and were debriefed about their experiences.

Materials and Procedure. Heart rate data were collected from the 38 participants during two epochs of time: 30-min baseline, recorded 1–3 h before the procession preceding the ritual; and during the ritual, from the beginning of the first fire-walk to the end of the last (28th) walk. (Note: analysis was carried out on all heart rate points during the 30-min ritual and not just the single points corresponding to the individual fire-walks.)

Each participant wore a Polar Team transmitter belt (http://www.polar.fi/en/products/team_sports/polar_team_system) around their chest, which measured their ECG and outputted instantaneous heart rate from interbeat intervals, which was averaged at 5-s intervals by the recording device. The transmitter belts were chosen because of their robustness and practicality: they were stable, easily transported, and were hidden under the clothes, and thus unobtrusive. The transmitter belts were synchronized in time via an interface-recharging unit, which was connected to a computer. The ritual was recorded using five different video cameras, to capture as many events and angles within the amphitheater. The video cameras were also synchronized to the time on the computer and were later used to mark all of the events, namely the beginning and end of the ritual and the timing of each fire-walk.

The ritual was one half-hour in length, starting with the first fire-walk and ending with the 28th. After crossing the fire, each walker was greeted at the other end of the burning coals by close relatives and friends. He/she would then be seated once again, and the next fire-walker would stand up and go through the same process, until all 28 walkers had crossed the fire. Of the 12 fire-walkers we measured heart rate from, 10 carried a close friend or relative on their backs while crossing the fire. Data were not collected from any of the carried participants.

Data Analysis. The data consisted of heart rates from three groups: 12 fire-walkers, nine related spectators, and 17 unrelated spectators. Each person's time series from the baseline and ritual epochs were 290 and 325 points in length, respectively. Two sets of analyses were computed: RQA on recurrence plots of individual data, and CRQA on cross-recurrence plots of paired participants' data, using the CRP MATLAB toolbox (38).

Recurrence plots. Recurrent behavior can be found in all natural processes and is a fundamental concept in dynamical systems theory. However, the recurrence of states can be difficult to visualize when the phase space of the given system is multidimensional. To allow for visualization of dynamical system recurrences (i.e., in 2D), recurrence plots were developed, first by Eckmann et al. (29).

A recurrence plot consists of a symmetrical square matrix with the same time-series along both the x and y axes. The plot represents every occasion at which a phase space trajectory goes through approximately the same region in the phase space, as marked by black dots. That is, when a trajectory visits the same area in phase space twice, a black dot is marked at the coordinates (i, j), where i is the x axis coordinate corresponding to the first time the trajectory visits that area in phase space, and j is the y axis coordinate corresponding to the time the trajectory revisits the area. Consequently there is also a black dot marked at the coordinates (j, i). A detailed description of this method can be found in a review by Marwan et al. (28). An accessible introduction can also be found in Riley and Van Orden (39).

The phase space was reconstructed via the time-delay method (40), whereby an embedding dimension and time delay first had to be chosen (28). The reconstructed phase space captures repetitive, chaotic, and singular behavior of a system over time and is the basis for the recurrence plot, which is the ultimate basis for the estimates of the dynamical characteristics of the time-series. Z scores of each member's heart rates were obtained, and the embedding parameters of delay and dimension were estimated for each data set separately. The embedding dimension was estimated using the false nearest neighbors algorithm, such that the parameter was increased in integer steps until the recruitment of nearest neighbors became unchanging (41), thus choosing the minimal sufficient dimension. In our analysis, this yielded values of 3 to 4. The time delay was estimated as the time of the first local minimum of the mutual average information function of the time-series, ranging from 3 to 21 for these time series. Last, a radius (or threshold) was chosen, which represents the radius of the neighborhood in which recurrent states are identified. Although there are several rules of thumb for the choice of a radius, we chose them separately for each data set, such that they corresponded to a fixed recurrence rate of 2% (28). The recurrence rate represents the percentage of data that are recurrent (i.e., the percentage of dark dots in the recurrence plot). The reason for keeping it fixed was to allow comparison between different data sets regarding the four parameters computed from the recurrence plots.

Recurrence quantification analysis. RQA is a method that was developed to quantify the small-scale structures in recurrence plots (30, 42–44). This technique allows quantification of different properties of the temporal evolution of a system, such as stability, complexity, and the occurrence of epochs of chaos vs. order in the behavior of the system (30). RQA has been applied successfully in physiology, especially for the investigation of heart dynamics (42, 45, 46).

Four different RQA quantities were compared: %DETerminism, MAXLine, Entropy, and Laminarity. These measures represent how patterned the data are in several regards (28). %DET quantifies the predictability of the time-series and is based on the recurrence point density and the diagonal line structures. It is calculated as the percentage of recurrent points that form diagonal lines in a recurrence plot (i.e., which are parallel to the central diagonal). Higher determinism with the same amount of recurrence implies stronger coupling. MAXLine is the length of the longest diagonal line in the recurrence plot that is not the main diagonal and quantifies the strength of the strongest attracting trajectory in the time-series. It represents the maximum time that two segments of the phase space trajectory are close to each other. It is inversely proportional to the largest Lyapunov exponent and thus represents a measure of the dynamical stability of the system. A shorter MAXLine implies a more chaotic, or less stable, signal. Entropy calculates the Shannon information entropy of a histogram of diagonal line lengths. It is an index of the complexity of the time series (47). Laminarity is the percentage of recurrent points forming vertical line segments and quantifies the amount of smoothness vs. chaoticity of the time-series. In simple terms, they represent the predictability, stability, complexity, and smoothness of the data, respectively.

These parameters were compared using a 3×2 mixed-model MANOVA, with the group as a between-subjects variable and the ritual vs. baseline as the within-subjects variable.

Cross-recurrence quantification analysis. CRQA is an analysis method used to explore the shared dynamics of two systems (31, 48, 49). It is based on cross-recurrence plots obtained from two one-dimensional time-series, which are a bivariate extension of recurrence plots. In this study, we therefore used CRQA to investigate the shared dynamics between three different pairs of participants: fire-walkers and related spectators, fire-walkers and tangentially related spectators, and fire-walkers and unrelated spectators. There were six spectators who were related to one of the fire-walkers that participated in the study, constituting the first group of pairs. The second group was chosen by keeping those same six spectators but repairing them with a different fire-walker chosen at random. The third group comprised the same fire-walkers from the first group, paired with a tourist spectator chosen at random.

Z scores were used once again for the baseline and ritual epoch data, and the same four measures were computed: %DET, MAXline, Entropy, and Laminarity. The recurrence rate was once again fixed at 2%, and the delay and dimension were taken as the average of the individual values from RQA. The four metrics were once again compared using the 3×2 mixed MANOVA, with "relatedness" as a between-subject variable and the ritual vs. baseline as the within-subject variable.

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1. Turner V (1967) *The Forest of Symbols: Aspects of Ndembu Ritual* (Cornell Univ Press, Ithaca, NY).
2. Rappaport R (1979) The obvious aspects of ritual. *Ecology, Meaning and Religion*, ed Rappaport R (North Atlantic Books, Richmond, CA), pp 173–221.
3. Sosis R, Ruffle BJ (2004) Ideology, religion, and the evolution of cooperation: Field experiments on Israeli Kibbutzim. *Res Econ An* 23:89–117.
4. Durkheim É (1995) *The Elementary Forms of Religious Life* (Free Press, New York).
5. Radcliffe-Brown AR (1952) *Structure and Function of Religious Life* (Cohen & West, London).
6. Whitehouse H (2004) *Modes of Religiosity: A Cognitive Theory of Religious Transmission* (AltaMira Press, Walnut Creek, CA).
7. Dunbar R (2006) We believe. *New Sci* 189:28–33.
8. Dunbar R, Barrett L, Lycett J (2005) *Evolutionary Psychology: A Beginner's Guide* (One World Press, Oxford).
9. Bernieri FJ (1988) Coordinated movement and rapport in teacher-student interactions. *J Nonverbal Behav* 12:120–138.
10. Isabella RA, Belsky J, van Eye A (1989) Origins of mother-infant attachment: An examination of interactional synchrony during the infant's first year. *Dev Psychol* 25:12–21.
11. Miles LK, Nind LK, Macrae CN (2009) The rhythm of rapport: Interpersonal synchrony and social perception. *J Exp Soc Psychol* 45:585–589.
12. Radcliffe-Brown AR (1922) *The Andaman Islanders* (Free Press, New York).
13. van Baaren RB, Holland RW, Kawakami K, van Knippenberg A (2004) Mimicry and prosocial behavior. *Psychol Sci* 15:71–74.
14. Wiltermuth SS, Heath C (2009) Synchrony and cooperation. *Psychol Sci* 20:1–5.
15. Cohen EE, Ejsmond-Frey R, Knight N, Dunbar RI (2010) Rowers' high: Behavioural synchrony is correlated with elevated pain thresholds. *Biol Lett* 6:106–108.
16. Hove MJ, Risen JL (2009) It's all in the timing: Interpersonal synchrony increases affiliation. *Soc Cogn* 27:949–961.
17. Chartrand TL, Bargh JA (1999) The chameleon effect: The perception-behavior link and social interaction. *J Pers Soc Psychol* 76:893–910.
18. Alcorta CS, Sosis R (2005) Ritual, emotion, and sacred symbols: The evolution of religion as an adaptive complex. *Hum Nat* 16:323–359.
19. Levenson RW (1994) Human emotions: a functional view. *The Nature of Emotion: Fundamental Questions*, eds Ekman P, Davidson RJ (Oxford Univ Press, New York), pp 123–126.
20. Armstrong L (1970) Fire-walking at San Pedro Manrique, Spain. *Folklore* 81:198–214.
21. Maughan RJ, Gleeson M (2008) Heart rate and salivary cortisol responses in armchair football supporters. *Med Sport* 12:20–24.
22. Leeka J, Schwartz BG, Kloner RA (2010) Sporting events affect spectators' cardiovascular mortality: It is not just a game. *Am J Med* 123:972–977.
23. de Vignemont F, Singer T (2006) The empathic brain: How, when and why? *Trends Cogn Sci* 10:435–441.
24. Jackson PL, Rainville P, Decety J (2006) To what extent do we share the pain of others? Insight from the neural bases of pain empathy. *Pain* 125:5–9.
25. Singer T, Lamm C (2009) The social neuroscience of empathy. *Ann N Y Acad Sci* 1156:81–96.
26. Gibbs RW, Van Orden GC (2003) Are emotional expressions intentional? A self-organizational approach. *Conscious Emotion* 4:1–16.
27. Hein G, Singer T (2008) I feel how you feel but not always: The empathic brain and its modulation. *Curr Opin Neurobiol* 18:153–158.
28. Marwan N, Romano MC, Thiel M, Kurths J (2007) Recurrence plots for the analysis of complex systems. *Phys Rep* 438:237–329.
29. Eckmann J-P, Oliffson Kamphorst S, Ruelle D (1987) Recurrence plots of dynamical systems. *Europhys Lett* 4:973–977.
30. Webber CL, Zbilut JP (2005) Recurrence quantification analysis of nonlinear dynamical systems. *Tutorials in Contemporary Nonlinear Methods for the Behavioural Sciences*, eds Riley MA, Van Orden GC (National Science Foundation, Arlington, VA), pp 26–95.
31. Shockley K, Butwill M, Zbilut JP, Webber CL (2002) Cross recurrence quantification of coupled oscillators. *Phys Lett A* 305:59–69.
32. Oullier O, de Guzman GC, Jantzen KJ, Lagarde J, Kelso JAS (2008) Social coordination dynamics: Measuring human bonding. *Soc Neurosci* 3:178–192.
33. Richardson MJ, Marsh KL, Schmidt RC (2005) Effects of visual and verbal interaction on unintentional interpersonal coordination. *J Exp Psychol Hum Percept Perform* 31:62–79.
34. Schmidt RC, O'Brien B (1997) Evaluating the dynamics of unintended interpersonal coordination. *Ecol Psychol* 9:189–206.
35. Bernardi L, et al. (2001) Effect of rosary prayer and yoga mantras on autonomic cardiovascular rhythms: Comparative study. *BMJ* 323:1446–1449.
36. Richardson MJ, Marsh KL, Isenhower RW, Goodman JR, Schmidt RC (2007) Rocking together: Dynamics of intentional and unintentional interpersonal coordination. *Hum Mov Sci* 26:867–891.
37. Schmidt RC, Carello C, Turvey MT (1990) Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. *J Exp Psychol Hum Percept Perform* 16:227–247.
38. Marwan N. (2010) Cross recurrence plot toolbox, 5.16. Available at http://www.agnld.uni-potsdam.de/~marwan/toolbox/.
39. Riley MA, Van Orden GC (2005) Tutorials in contemporary nonlinear methods for the behavioural sciences. Available at: http://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp. Accessed June 27, 2009.
40. Takens F (1981) Rand DA, Young LS (1981) Detecting strange attractors in turbulence. *Dynamical Systems and Turbulence* (Springer, Berlin), Vol 898, pp 366–381.
41. Kennel MB, Brown R, Abarbanel HD (1992) Determining embedding dimension for phase-space reconstruction using a geometrical construction. *Phys Rev A* 45:3403–3411.
42. Marwan N, Wessel N, Meyerfeldt U, Schirdewan A, Kurths J (2002) Recurrence-plot-based measures of complexity and their application to heart-rate-variability data. *Phys Rev E Stat Nonlin Soft Matter Phys* 66:026702.
43. Webber CL, Jr., Zbilut JP (1994) Dynamical assessment of physiological systems and states using recurrence plot strategies. *J Appl Physiol* 76:965–973.
44. Zbilut JP, Webber CL (1992) Embeddings and delays as derived from quantification of recurrence plots. *Phys Lett A* 171:199–203.
45. Schumacher AM, Zbilut JP, Webber CL, Jr., Schwertz DW, Piano MR (2006) Detection of cardiac variability in the isolated rat heart. *Biol Res Nurs* 8:55–66.
46. Zbilut JP, Webber CL (1998) Quantification of heart rate variability using methods derived from nonlinear dynamics. *Analysis and Assessment of Cardiovascular Function*, eds Drzewiecki G, Li JKJ (Springer, New York), pp 324–334.
47. Pellecchia GL, Schockley K (2005) Application of recurrence quantification analysis: influence of cognitive activity on postural fluctuations. *Tutorials in Contemporary Nonlinear Methods for the Behavioural Sciences*, eds Riley MA, Van Orden GC (National Science Foundation, Arlington, VA), pp 95–141.
48. Marwan N, Kurths J (2002) Nonlinear analysis of bivariate data with cross recurrence plots. *Phys Lett A* 302:299–307.
49. Zbilut JP, Giuliani A, Webber CL (1998) Detecting deterministic signals in exceptionally noisy environments using cross-recurrence quantification. *Phys Lett A* 246:122–128.