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Religious rituals in the United Kingdom and Brazil are associated with increased social bonding and pain threshold

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From an evolutionary perspective, large-scale human groups face an adaptive challenge: maintaining cohesion beyond the limits of one-to-one grooming. Cultural practices that recruit evolved bonding systems may help solve this problem by harnessing mu-opioid psychobiological mechanisms. Religious rituals are cultural practices that consistently promote social cohesion, and here we report a pre-registered large-scale field study examining psychobiological mechanisms underlying these rituals. Participants were tested in the United Kingdom and Brazil at 24 ritual sites (N = 265), with measures taken pre- and post-ritual. Results showed that levels of social bonding (5.4% increase, $r_R = 0.30$) and positive affect (13.1% increase, $r_R = 0.27$) were higher after ritual participation. Importantly, increased social bonding was independently predicted by increases in pain threshold (a proxy for mu-opioid activation; $\beta = 0.13$, $R^2 = 0.02$), positive affect ($\beta = 0.25$) and connection to a higher power ($\beta = 0.15$), even after controlling for country, gender, age and religiosity ($R^2 = 0.15$). This multi-site field study provides experimental yet naturalistic evidence that religious rituals recruit an evolved mu-opioid-based affiliation system that may help sustain cohesion in large congregations, supporting the brain-opioid theory of social attachment.

1. Introduction

How do humans maintain cooperative ties and mutual commitment in groups that are far larger than those in which primate-like grooming can effectively sustain bonds? There are limits to what can be achieved via one-to-one affiliative behaviours such as grooming, which directly influence the neurochemical mechanisms supporting bonding [1,2]. Religious rituals have been proposed as one set of cultural practices that solve this adaptive problem by exploiting evolved neurochemical systems for social bonding in a scalable way [3], through the inclusion of opioid- and bonding-inducing behaviours, allowing cohesion to be maintained within large coalitions [1].

Machin & Dunbar [1] proposed the 'brain-opioid theory of social attachment' (BOTSA) to explain how one-to-one grooming and similar behaviours

allow primates to create and maintain social bonds. BOTSA adapted Panksepp's theory that endogenous opioids are the biochemical mechanism behind feelings of bonding [4,5], with a main focus on mu-opioids [1]. Extensive neurochemical work in animals and humans shows that mu-opioids play a central role in animal social bonding [6–8] as well as human adult social bonding [2,9,10].

BOTSA proposes that humans have developed behaviours that, much like grooming, encourage the release of mu-opioids in larger groups of people than can be reached by primate-like touch-based social grooming. The main behaviour that stimulates social bonding is synchronized movement, sometimes in the form of music-making [11–17], with other behaviours, such as feasting consumption [18,19], also playing a role. These behaviours have an advantage over grooming behaviours as they can affect larger groups as opposed to being one-on-one, making it a far more time-efficient way of encouraging bond formation and maintenance. Thus, religious rituals may be particularly effective at the formation and maintenance of social bonds, because they incorporate a range of specific opioid- and bonding-inducing behaviours, such as singing [20,21], dancing [14,22] and shared goals [23], among others (e.g. [24]).

In the present study, we test the claim that religious rituals reliably encourage the release of endogenous opioids, specifically mu-opioids, which may have promoted the expansion and maintenance of large-scale human social groups [25]. To do this, we conducted a cross-cultural field study of 24 Christian and Afro-Brazilian rituals, using questionnaire measures and pain tolerance (a proxy for opioid activation). The current literature on rituals suggests that attendees often claim to feel a connection with others in attendance [26–30]. However, religious rituals vary widely both within and between religious traditions. They can be a simple ritualized meal or a short prayer, ranging from a short prayer to extreme body piercing.

Religious rituals likely encourage mu-opioid release through two processes. First, rituals incorporating overtly painful or physically demanding experiences, such as fire walking [30,31] or body piercing [32], engage the endogenous opioid system directly via nociceptive activation. This stress-induced analgesia is not purely a private physiological response; the shared nature of the ordeal appears to amplify bonding because the pain is endured collectively and the resulting opioid release occurs within a social context that frames suffering as meaningful [26]. This may help explain why extreme rituals produce strong feelings of bonding and commitment between participants [32].

Second, coordinated synchronized behaviours, such as communal singing, rhythmic prayer and collective movement, have been proposed to recruit opioid-mediated bonding pathways [14,33,34]. Synchronized movement and music-making produce positive affect and a sense of merged self-other boundaries [35], which in turn stimulates endogenous opioid release and lowers pain thresholds, creating conditions for affiliation [20,21]. Religious rituals may be especially effective compared with other synchronized activities, such as watching a sporting event together, because they combine synchrony with shared intentionality [23], shared sacred goals and connection to a transcendent agent or higher power [3]. These additional elements may amplify the affiliative signal by embedding the synchronized experience within a framework of collective meaning and identity that extends beyond the immediate social context [36].

Previous studies have been conducted during what has been described as 'imagistic' (higher-intensity, low-frequency) modes of religious ritual expression [37]. High-intensity rituals are likely to have an immediate impact [38], whereas doctrinal rituals that are of lower intensity but higher frequency may rely more on synchronized behaviours. However, no prior study has directly measured group social bonding during naturalistic doctrinal rituals.

Moreover, while some research has sought to understand the mechanisms underlying ritual social bonding in the field (e.g. [39]), field research on mu-opioid mechanisms remains rare [40]. This is likely because the body's main mu-opioid agonist, β-endorphin, does not readily pass through the blood–brain barrier [41], making direct field measurements impossible, as they require invasive procedures such as spinal tap. However, since mu-opioids act as a natural analgesic [42,43], a common solution is to use pain threshold and/or pain tolerance as proxy measures for mu-opioid release in experimental research [13,33,44].

(a) The present study

In the current study, we conducted a field study of 24 religious rituals in the United Kingdom (UK) and Brazil, where levels of social bonding and pain threshold—as a proxy for opioid release—were measured both before and after the rituals. We also measured affect before and after the rituals, as research suggests that emotional state is related to both pain perception [45] and changes in opioid tone [46], and that positive affect plays a role in social bonding [47].

Psychology has a history of only studying individuals from Western, educated, industrialized, rich, democratic populations [48], particularly white, middle-class university students. This is especially true in the psychobiology of social bonding (see [49] for one such criticism), though the cognitive and evolutionary science of religion has made improvements [50], as has recent cross-cultural work on ritual and music [51]. Sampling from both the UK and Brazil addresses these concerns [40]. Including an Afro-Brazilian religion native to the research context also supports ecological validity and ensures research is conducted in-situ rather than in a 'white room' [50].

The first aim of this study was to test whether feelings of group social bonding increase from before to after doctrinal rituals. The second aim was to provide evidence that μ-opioid activation (as measured via pain threshold proxy) is related to group social bonding within religious ritual. The pre-registered hypotheses we will analyse here were as follows: (i) social bonding will be higher after than before the religious ritual (see effect 'a' in figure 1); (ii) pain threshold will be higher after than before the religious ritual (see effect 'b' in figure 1); (iii) increases in pain threshold will predict increase in social bonding (see effect 'c' in figure 1).

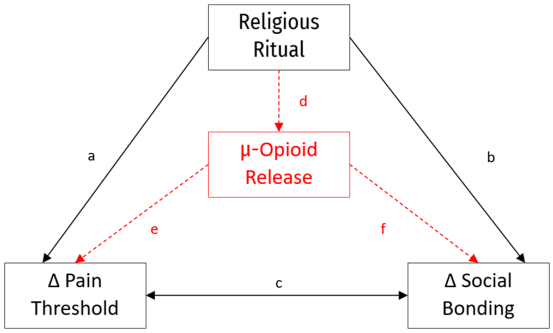

Figure 1. The pathways of the theorized mechanisms of action for how religious ritual would be associated with changes in feelings of social bonding.

2. Methods

(a) Participants

Participants were recruited from 13 Christian churches of different denominations in the UK (London, Coventry, Oxfordshire) and 11 Afro-Brazilian (Umbanda) religious groups in Brazil (São Paulo and Porto Alegre). All participants were aged 18 and over. In total, 359 (M_{age} = 44.3 years, s.d.$_{age}$ = 17.3, 246 women) participants were recruited across the UK (n = 113, M_{age} = 58.6 years, s.d.$_{age}$ = 17.2, 77 women) and Brazil (n = 246, M_{age} = 38.0 years, s.d.$_{age}$ = 13.4, 169 women). Of these, 91 participants met at least one exclusion criterion (see below), which left 265 total participants (M_{age} = 42.3 years, s.d.$_{age}$ = 15.5, 180 women), 70 UK participants (M_{age} = 54.6 years, s.d.$_{age}$ = 17.2, 47 women) and 195 Brazilian participants (M_{age} = 37.9 years, s.d.$_{age}$ = 12.1, 133 women). All data analysis was conducted after data collection had finished.

Pain threshold data were not collected for participants with a diagnosis of arthritis [52], diabetes [53] and/or attention-deficit/hyperactivity disorder [54], due to differences in pain perception. Given natural fluctuations that alter the release of mu-opioids during pregnancy [55], pregnant participants were also excluded. We also controlled for recent alcohol intake [56] and pain medication as additional exclusion criteria after data collection, given the effects of alcohol and pain medications on pain perception. Finally, a pre-session pain threshold measurement of the upper-limit value of 300 mmHg was used as an exclusion criterion, as no upward change can be detected.

In the pre-registration, an *a priori* power analysis suggested 226 participants were needed for the pre-planned analysis, but given changes in the analyses, this was no longer appropriate. Using G*Power [57], it was determined by conducting an 'Exact' linear, two-tailed regression test to find this effect, with H1 p^2 = 0.08 and H0 p^2 = 0, α = 0.05, power $(1 - \beta)$ = 0.8 with a single predictor, 115 participants would be sufficient. We also conducted a linear mixed-effects analysis. The calculation of power for a three-level mixed-effects model, while possible [58], is not simple. The electronic supplementary material provides an expanded discussion of mixed-model power (§1.1). In short, there are instances where 17 top-level objects would be appropriate. The data from this study likely conforms to these instances, and so 24 ritual sites should suffice to find effects using mixed-effects modelling.

(b) Context

The UK religious rituals were all Christian but from varying denominations, including Roman Catholic, Methodist, Church of England, Baptist and those that self-described as 'Evangelical'. While the exact nature of the content of the rituals differed, all of the UK church rituals included: (i) time spent praying, (ii) communal singing while both seated and standing, (iii) periods of time where a leader (e.g. priest or minister) spoke from a lectern, pedestal or pulpit, (iv) a moment of silence, and (v) a period of time where congregants were encouraged to communicate with one another (often via wishes for peace to be brought upon one another).

Umbanda is an Afro-Brazilian religion that blends spiritualism, African ritual dances and rhythms and Roman Catholic prayers and images. While there are variations in beliefs across Umbanda groups, there are many commonalities such as the belief in a supreme creator and the syncretization of sub-deities with Christian saints [59]. Another common belief is the ability to contact spirits via mediums. Umbanda rituals include: (i) time spent praying, (ii) time spent communal singing, (iii) dancing or clapping, (iv) time spent with a ritual leader speaking to the congregation, and (v) time spent communicating with the spirits in some way [60,61].

Despite significant differences in the belief systems of the UK and Brazilian rituals, some clear similarities are present: the presence of prayer, communal singing, time spent focusing on an individual speaker directing their attention to the congregation and ritualized standing and sitting. It is these common ritual behaviours that are hypothesized to be associated with increases in feelings of social bonding [25].

(c) Materials

Social bonding. Six questions were used. Five of these were measured on a 7-point Likert scale, from '1' 'not at all' to '7' 'extremely': (i) 'At this moment, how connected do you feel to the people in your congregation?' (adapted from [17]); (ii) 'At this moment, how emotionally close do you feel to the other members of your congregation as a whole'; (iii) 'Thinking about

everyone in your congregation now, how much do you trust the others in this group?"; (iv) 'How much do you like the people in your congregation overall?' (adapted from [62]; and (v) 'Thinking about everyone in your congregation now, do you feel you have a lot in common with others in this congregation?' (adapted from [63]. The last question was the pictorial Inclusions of Others in Self scale (IOS [64]), a measure of self–other overlap that consists of a 7-point scale using Venn diagrams to illustrate how closely one identifies with others, where '1' signifies mostly separate identity and '7' signifies extremely close identity. Answers to these questions were averaged into a single social bonding score (see §3). A full version of the questionnaire can be found on Open Science Foundation (OSF; https://doi.org/10.17605/OSF.IO/WAM9Z).

Pain threshold. This was measured using a 'pressure cuff' (typically used to measure blood pressure), which involved slowly inflating a sphygmomanometer cuff on the participant's upper, non-dominant arm at 10 mmHg intervals each second until the participant indicated that they were 'very uncomfortable'. The measurement was recorded out of sight of the participant. The 'score' on this test is the pressure (in mmHg), which is listed on the sphygmomanometer when a participant signalled to the researcher that they were very uncomfortable. This measure of pain threshold has previously been used in similar field and experimental studies (e.g. [33,65,66]), and manual pressure-pain threshold measures have high levels of test–retest reliability [67,68]. The validity of this proxy is further supported by naloxone blockade studies, which show that opioid antagonism can modulate pressure-pain sensitivity [69,70], consistent with a contribution from endogenous mu-opioid signalling. Moreover, pain threshold was used over pain tolerance due to an abundance of evidence suggesting a link between threshold, but not tolerance, with mu-opioid release (e.g. [71,72]). The pressure-pain threshold is taken both before and after the ritual, with the difference in pressure taken as the change in threshold (ΔPT). For the full cuff measure protocol, see the protocol on OSF (https://doi.org/10.17605/OSF.IO/WAM9Z).

Affect. The Positive And Negative Affect Scale (PANAS [73]) was used to collect data on the affective state of participants both before and after the ritual. The PANAS asks participants to say how much they are feeling 20 emotions (10 positive, 10 negative) 'at this moment' measured on a 6-point Likert scale, from zero to five, where zero is 'not at all' and five is 'very much'. The values were summed for positive affect and negative affect, separately.

Religiosity. Participants were asked how long they had attended their current church, and their religiosity was measured with the Duke University Religion Index (DUREL [74]). While the DUREL was conceptualized to measure organized religious activity, non-organized religious activity and intrinsic religiosity most empirical assessments of DUREL, in both English and other languages, have found a single-factor solution is most appropriate [75,76], including in Brazilian populations [77]. Participants were also asked after the ritual, a measure of 'connectedness to God' during the ritual: 'During today's ritual, did you feel connected to God, Jesus and/or the Holy Spirit?' In Brazil, 'spirit guides' was added to the question. The researchers also collected information such as size of group, length of ritual and religious denomination for follow-up analyses to check for confounds.

Other measures. The questionnaire given to participants contained further questions, but these were included for use in a separate research project concentrating on secular versus religious ritual attendance, with a focus on morality [78].

(d) Translation

For measures to be translated into Brazilian Portuguese, we used previous validated translations, and remaining translations were done by fluent speaker co-authors using a check-translate procedure (see electronic supplementary material).

(e) Procedure

Participants were made aware of our field study via newsletters and announcements at their respective religious groups. On the day of the study, after reading the participant information sheet and signing the consent form, participants first did the pressure cuff measure, followed by the pre-ritual questionnaire as detailed above. After the ritual, participants had the pressure cuff measure taken again by the same researcher who took it before (to keep extraneous variables for this measurement as consistent as possible), and then filled out the post-ritual section of the questionnaire. Participants were then partly debriefed about the study. A full debriefing was sent out to all participating religious communities once we finished all data collection. For a full explanation of the process of church recruitment and a full outline of the study procedure, see procedures on OSF (https://doi.org/10.17605/OSF.IO/WAM9Z). Data were collected between 2018 and 2019.

(f) Data analysis

This study has been pre-registered on the OSF (https://doi.org/10.17605/OSF.IO/QZSGB). Three changes were from the pre-registration: (i) affect was added as a variable of interest; (ii) behavioural synchrony could not be assessed due to differences in video recording quality across sites (see electronic supplementary material); and (iii) given the data's hierarchical structure, with measurement occasion (level 1) nested within participants (level 2) nested within ritual site (level 3; see electronic supplementary material, figure S1B), linear mixed-effects models were used.

For the regression analyses, data were first tested for multivariate normality, autocorrelation and homoscedasticity. These assumptions were met. Variables were mean-centred and standardized to create *Z*-scores as appropriate for the purpose of the regression analysis. As the pre-registration did not specify what would constitute a multivariate outlier, no outliers were excluded in this analysis. As part of data analysis, non-parametric tests were required due to non-normality of the data (for more information on this and on statistical methods and power analyses, see the electronic supplementary material). All anonymized data and R [79] analysis script can be found on the OSF online repository (https://doi.org/10.17605/OSF.IO/WAM9Z).

3. Results

(a) Social bonding

Prior to computing a social bonding composite, an exploratory factor analysis was conducted on the five non-IOS questions at each time point to verify unidimensionality prior to averaging. Using an oblique rotation and a principal-axis method for extraction, both the pre-ritual and post-ritual responses yielded a single-factor solution (pre: 62.15% variance explained; post: 71.48%), with all items loading on one factor and no eigenvalue exceeding 1.0.

Internal reliability was good at both time points (pre: $\omega = 0.85$, 95% confidence interval (CI) [0.81, 0.87]; post: $\omega = 0.90$, 95% CI [0.87, 0.92]). The five-item average correlated moderately to strongly with the IOS (pre: $r = 0.69$; post: $r = 0.67$), supporting construct validity. The IOS was therefore added to create a six-item composite, which again yielded a single-factor solution and good reliability (pre: $\omega = 0.87$; post: $\omega = 0.90$). This composite was used in all subsequent analyses.

(b) Effects of religious ritual

A Shapiro–Wilk test was conducted to check whether the data met the assumptions for parametric testing. The social bonding ($W = 0.96$, pre-ritual, $W = 0.93$, post-ritual), pain threshold ($W = 0.97$, $W = 0.97$), positive affect ($W = 0.96$, $W = 0.97$) and negative affect ($W = 0.930$, $W = 0.86$) scores were all significantly different from normally distributed (all $p < 0.001$). Thus, non-parametric tests were used.

Two-tailed Wilcoxon signed-rank tests were used to test pre-to-post changes (see electronic supplementary material, table S1C). As predicted, social bonding was higher post-ritual ($M = 5.70$, s.d. = 0.92) than pre-ritual ($M = 5.41$, s.d. = 0.94, $p < 0.001$, $r_R = 0.30$) and pain threshold scores were higher post-ritual ($M = 178.63$, s.d. = 60.35) than pre-ritual ($M = 157.90$, s.d. = 54.45, $p < 0.001$, $r_R = 0.27$), indicating a small-to-moderate effect of ritual attendance on pain threshold. Positive affect increased from pre-ritual ($M = 38.71$, s.d. = 11.90) to post-ritual ($M = 39.78$, s.d. = 12.12, $p = 0.02$, $r_R = 0.12$), indicating a small effect, and negative affect decreased from pre-ritual ($M = 11.24$, s.d. = 7.34) to post-ritual ($M = 8.87$, s.d. = 5.57, $p < 0.001$, $r_R = 0.33$), indicating a moderate effect. All pre-to-post changes remain significant when correcting for multiple comparisons using the Bonferroni correction.

Results were largely consistent across countries, with two exceptions (see electronic supplementary material, table S1C): pain threshold did not significantly increase following ritual in the UK sample ($p = 0.058$), and positive affect did not significantly increase in the Brazil sample ($p = 0.68$). Figure 2 displays the distribution of scores for each country at both time points, illustrating the pre-to-post changes reported in electronic supplementary material, table S1C.

(c) Relationship between social bonding and pain threshold

Figure 3 plots the change in social bonding against the change in pain threshold. A simple linear regression was performed to determine whether the change in pain threshold (ΔPain threshold) predicted the change in social bonding score. ΔPain threshold significantly predicted change in social bonding score ($F_{1,264} = 4.846$, $p = 0.029$, $R^2 = 0.018$, $R_{adj}^2 = 0.014$), where ΔPain threshold accounted for 1.8% of the variance in the change in social bonding score.

As a follow-up to the pre-registered hypothesis, and to examine whether change in affect also predicted change in social bonding, a multiple regression was conducted. We found a significant model ($F_{3,262} = 9.17$, $p < 0.001$, $R^2 = 0.095$, $R_{adj}^2 = 0.085$), where change in pain threshold, positive affect and negative affect were all significant predictors of change in social bonding score (see table 1).

A further follow-up analysis was conducted to control for age, country, gender, religiosity, connectedness to God and the number of years they had attended the service for. This model was significant ($F_{9,233} = 4.47$, $p < 0.001$, $R^2 = 0.15$; see table 2). Change in social bonding was significantly predicted by change in pain threshold, positive affect and negative affect and feelings of connection to God.

As affect, age and gender have been known to influence pain perception [80,81], another multiple regression was conducted with positive affect, negative affect, gender and age included as predictors, to determine whether pain threshold change was itself predicted by possible control variables. This model was not significant ($F_{4,260} = 0.62$, $p = 0.646$, $R^2 = 0.01$). This suggests that pain threshold change was not predicted by change in affect or by the variables age or gender.

(d) Multi-level models

As the data in this study have a hierarchical structure (measurement occasions, within participants, within ritual sites), a series of follow-up analyses were conducted using a linear mixed-model approach. Suggestions provided by Aho *et al*. [82] and Luke [83] on how to conduct mixed-effects model analysis were followed (for a detailed rationale and method of how this was implemented, see the electronic supplementary material sheet).

A series of models was created, and the corrected Akaike information criterion (AICc) [84] was used to select the best-fit model. These models were compared with one another to find the most parsimonious model (the one with the lowest AICc value) and then determine the significance of fixed effects. The best way to get a more reliable *p*-value is to fit the model using a 'reduced maximum likelihood' instead of a maximum likelihood method [83]. The analysis script detailing the steps and a full report can be found in the electronic supplementary material.

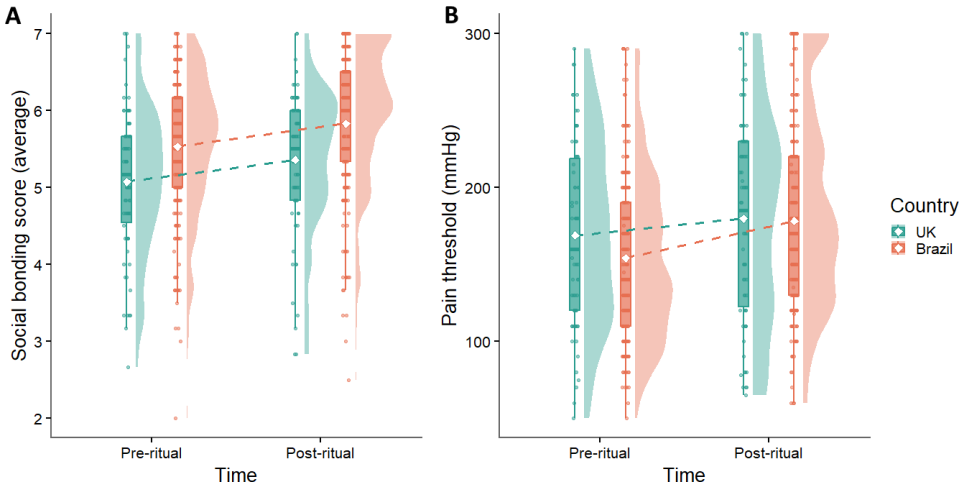

Figure 2. Raincloud plots displaying social bonding scores (A) and pain threshold in mmHg (B) for UK and Brazil participants at pre- and post-ritual time points. Each plot displays the distribution of individual scores (half-violin), a boxplot (median, interquartile range and whiskers extending to 1.5× interquartile range) and individual data points. Dashed lines connect group means (white diamonds) from pre- to post-ritual for each country. UK: $n = 70$; Brazil: $n = 195$.

Table 1. Multiple linear regression predicting change in social bonding with change in pain threshold and change in positive and negative affect scores.

variable	*β*	95% CI	*t*	*p*
Δpain threshold	0.14*	[0.03, 0.26]	2.45	0.01
Δpositive affect	0.22***	[0.10, 0.33]	3.69	<0.001
Δnegative affect	−0.18**	[−0.30, −0.06]	−3.05	0.003

Note: $R^2 = 0.09$**, 95% CI = [0.03, 0.16]. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Table 2. Multiple linear regression predicting change in social bonding using change in pain threshold and change in positive and negative affect scores and additional variables.

variable	*β*	95% CI	*t*	*p*
Δpain threshold	**0.14***	[0.02, 0.26]	2.23	**0.03**
Δpositive affect	**0.25*****	[0.13, 0.38]	4.05	**<0.001**
Δnegative affect	**−0.20****	[−0.33, −0.08]	−3.31	**0.001**
country	−0.17	[−0.50, 0.17]	−0.98	0.33
connection to God	**0.15***	[0.01, 0.29]	2.05	**0.04**
age	−0.04	[−0.19, 0.10]	−0.60	0.55
service attendance	−0.04	[−0.18, 0.09]	−0.66	0.51
gender	−0.11	[−0.37, 0.14]	−0.87	0.39
religiosity	−0.04	[−0.18, 0.09]	−0.66	0.51

Note: $R^2 = 0.15$**, 95% CI = [0.05, 0.20]. Signicant *β*-values in bold. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

After a series of multi-level models were compared, the most parsimonious model included an interaction effect between country and positive affect in addition to the following variables: pain threshold, positive affect, negative affect, country, connection to God, age, service attendance, gender and religiosity. We then used Luke's [83] method to find the significant fixed effects, the results of which are presented in table 3. There were significant fixed effects of measurement occasion (pre- versus post-ritual), pain threshold, positive and negative affect, a feeling of a connection to God, religiosity, and we found a significant interaction effect between positive affect and country, where social bonding was predicted by positive affect more strongly in the UK than in Brazil.

Using the same multi-level modelling analysis method, we also found predictors of pain threshold. The most parsimonious model included measurement occasion, social bonding, gender, country, religiosity interactions between measurement occasion and social bonding and measurement occasion and gender. Inclusion of positive affect, negative affect, age and/or connection to God led to a worse model fit. In the final model, measurement occasion was a significant positive predictor of pain threshold ($t(238.9) = 3.28$, $p = 0.001$), while gender ($t(330.2) = -2.25$, $p = 0.025$) and religiosity ($t(245.5) = -2.99$, $p = 0.003$) were significant negative predictors of pain threshold. However, no interaction effects were significant. Here, post-ritual pain threshold was significantly higher than pre-ritual pain threshold, those who identified as women had significantly lower pain thresholds than those who identified as men, and a higher religiosity score was significantly predictive of a lower pain threshold.

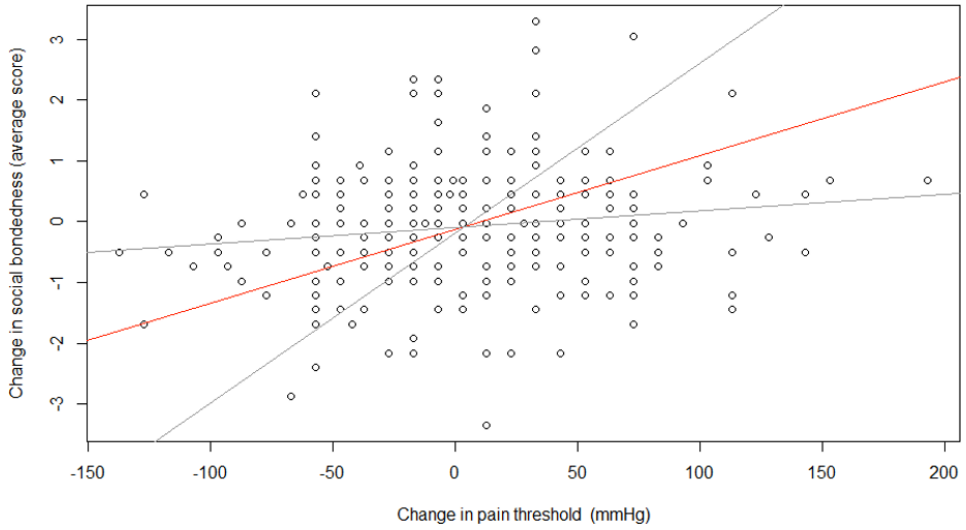

Figure 3. Scatterplot with change in pain threshold against change in social bonding; the light grey lines represent the 95% confidence interval of the RMA regression line (shown in red).

Table 3. Multi-level linear model output from the most parsimonious multi-level model predicting social bonding, using the Satterthwaite [85] correction (see [83]).

fixed effects	β	s.e.	95% CIs	t	p	d.f.
(intercept)	0.06	0.08	[−0.09, 0.20]	0.76	0.46	26.77
measurement (1 = post)	**0.07****	0.02	[0.03, 0.12]	3.09	**0.002**	279.99
pain proxy mu-opioids	**0.11****	0.04	[0.04, 0.18]	2.90	**0.004**	456.11
country (1 = Brazil)	0.15	0.09	[−0.02, 0.32]	1.78	0.08	75.14
positive affect	**0.27*****	0.05	[0.18, 0.36]	5.88	**<0.001**	465.27
negative affect	**−0.19*****	0.05	[−0.28, −0.11]	−4.32	**<0.001**	374.47
connection to God	**0.17****	0.06	[0.06, 0.29]	2.87	**0.004**	251.98
gender	0.04	0.05	[−0.05, 0.13]	0.83	0.41	228.39
age	0.06	0.06	[−0.06, 0.17]	0.96	0.34	239.08
religiosity	**0.19*****	0.05	[0.09, 0.30]	3.55	**<0.001**	234.90
country * positive affect	**−0.10***	0.05	[−0.20, −0.01]	−2.17	**0.03**	438.50
random effects						
σ^2	0.20					
$\tau_{00\ ParticipantID:ChurchID}$	0.40					
$\tau_{00\ ChurchID}$	0.06					
ICC	0.70					
$N_{Participant}$	240					
$N_{ChurchID}$	24					
observations	480					
marginal/conditional R^2 [a]	0.31/0.79					

Note. Reference levels are: measurement (0 = pre), Country (0 = UK). Significant β-values in bold. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. [a] Marginal R^2 shows the amount of variance explained by only the fixed effects, and conditional R^2 shows the amount of variance explained by the full model (fixed effects and random effects together).

4. Discussion

In this fieldwork study measuring 24 naturally occurring rituals, we provide field evidence consistent with the 'brain-opioid theory of social attachment' [1,3]. Participation in rituals was followed by increased feelings of social bonding, and these changes were predicted by a concurrent increase in a mu-opioid-linked proxy (pressure-pain threshold) alongside shifts in affect. Together, these findings are consistent with the idea that routine religious services actively engage opioid- and bonding-inducing processes that help sustain cohesion within large congregations, thus providing further evidence for the BOTSA model as regards the role of mu-opioids in social bonding [25].

Specifically, we found that social bonding was higher following religious rituals, and that this was predicted by a concurrent increase in pain threshold and positive affect and a decrease in negative affect. This pattern suggests that ritual bonding is supported by at least two partially independent but converging pathways: a mu-opioid-linked mechanism indexed by changes in pain threshold, and affective processes that shift participants towards a more positively valenced, less negatively aroused state. In line with broaden-and-build models of positive emotion, such positive affective shifts may temporarily expand individuals' cognitive and behavioural repertoires in ways that facilitate approach, play and openness to others, thereby building enduring social resources and strengthening bonds within the congregation [47,86].

In addition, a substantial body of work shows that affect modulates pain perception and opioid tone: positive emotional states and appetitive motivation generally dampen pain, whereas negative affect and threat heighten it, often via interactions between emotional appraisal, attention and endogenous analgesic systems, including opioidergic pathways [45,46]. Our findings are consistent with this literature in suggesting that ritual-induced changes in positive and negative affect may directly promote feelings of closeness and contribute indirectly by modulating mu-opioid-mediated analgesia, with both channels jointly supporting the experience of group social bonding during doctrinal rituals.

The role of oxytocin also warrants consideration. Oxytocin is a neuropeptide associated with social affiliation and pair bonding in animal models, and early human studies suggested a role in interpersonal trust [87]. A subsequent meta-analysis of the oxytocin-trust literature found an overall effect size indistinguishable from zero [88], and the broader body of human research has been described as the 'oxytocin paradox', a pattern of inconsistent findings marked by context-dependency and gender differences [89–91]. A genomic study of six neurotransmitter systems found that oxytocin receptor genes were associated only with romantic pair bonding, not with general group social bonding [13]; mu-opioid receptor genes showed the most generalized association across all bond types, including group bonds. Oxytocin is therefore a less compelling candidate for explaining the congregational bonding effects observed here.

That said, oxytocin may interact with the mu-opioid system: central oxytocin signalling can stimulate endogenous opioid release, and mu-opioid activation modulates oxytocin-sensitive circuits involved in social reward [10,46]. There is also evidence that oxytocin pathways in humans are associated with positive affect and spirituality [92], which may be relevant given the connection-to-God effects observed here. Disentangling the respective contributions of these systems would require pharmacological manipulation of both pathways simultaneously.

This study is, to our knowledge, the first to show that religious ritual increases mu-opioid activation as indexed by a pain threshold assay, although we acknowledge that pain threshold is only a proxy measure. This limitation can be addressed with pharmacological blockade of mu-opioid receptors, for example, using Naltrexone (e.g. [93]). Since this study was conducted, other research has shown that indeed, blocking mu-opioid receptors with Naltrexone leads to significantly lower feelings of social bonding during ritual compared with placebo, across both a yoga-based ritual in the UK and an Umbanda ritual in Brazil, providing direct pharmacological evidence that mu-opioids play a causal role in ritual-induced social bonding [94]. Nonetheless, mu-opioid system activity does not always have a reliably detectable or straightforward influence on the measurement of pain thresholds. Werner *et al*. [95] found that mu-opioid receptor (MOR) antagonist effects on pain threshold were inconsistent across a broad range of experimental paradigms, including 'inhibitory' and 'sensitising' test models, which likely reflects the diversity of designs and pain modalities reviewed rather than undermining pressure-pain threshold specifically. Direct neurochemical measures, such as positron emission tomography imaging of mu-opioid receptor binding, would provide stronger evidence for the proposed mechanism in future work.

The modest variance explained by pain threshold change in isolation is consistent with field studies of opioid-mediated bonding [14,20] and likely reflects the substantial individual variability inherent to naturalistic measurement rather than being biologically trivial. When modelled alongside affect and other covariates, the independent contribution of the pain proxy remains significant, consistent with a genuine but incremental opioid contribution to the bonding response. Although women showed lower absolute pain thresholds than men overall, gender did not predict the magnitude of pain threshold change during the ritual, nor did it moderate the relationship between pain threshold change and social bonding change, suggesting the opioid-linked bonding pathway operates similarly across the genders in this sample.

Our findings are consistent with BOTSA [1], though they sit within an ongoing debate about the mechanisms linking ritual behaviour, synchrony and social bonding. Some researchers have raised challenges to synchrony effects; Atwood *et al*. [96] argued that many experimental synchrony-bonding studies are vulnerable to expectancy effects, whereby participants infer they are supposed to feel more connected. However, Tunçgenç *et al*. [97] responded directly and showed that synchrony-prosociality effects persist under conditions designed to control for expectancy, suggesting the relationship is not reducible to demand characteristics alone. Moreover, a meta-analysis by Rennung & Göritz [98] found that prosocial effects of synchrony are reliable but modest and context-dependent, which is consistent with our finding that pain threshold change explained a small but independent portion of variance in social bonding change after controlling for affect, country, gender, age and religiosity.

However, since we could not measure synchrony directly due to technical issues with video recording, our findings are best interpreted as evidence for the broader ritual activity effect rather than a synchrony-specific one. Nevertheless, experimental work has shown that synchrony adds an independent increment to pain threshold and social bonding over and above the effect of the activity itself [14,33,44], such that ritual participation alone is likely to produce an opioid-linked bonding effect, with synchrony amplifying but not driving it.

Religious rituals incorporate synchronized behaviours, including communal singing and collective movement, each of which has been proposed to serve evolutionary functions. Mehr *et al*. [99] argue that music may primarily serve credible signalling or coalition-display functions, whereby participants demonstrate commitment to the group. Savage *et al*. [100] propose a related but distinct account, the Music and Social Bonding hypothesis, arguing that music evolved as a derived bonding mechanism that augments ancestral bonding mechanisms such as grooming by allowing bonds to be maintained with multiple individuals

simultaneously, building on BOTSA. BOTSA proposes that ritual participation (which may involve synchrony) evolved as a scalable bonding mechanism because it activates the opioid system in ways that dyadic grooming cannot achieve at scale [1,101]. The present study does not adjudicate between these accounts but provides field evidence consistent with the opioid pathway BOTSA proposes.

We initially did not find that participants' level of religiosity or length of time they had attended the ritual had an added effect in predicting an increase in social bonding. This suggests that, in the short term, the bonding effects of doctrinal rituals may be relatively robust across individuals with differing religious histories, at least when they are already embedded enough in the community to attend services. However, follow-up multi-level analyses revealed that higher religiosity was associated with higher overall levels of social bonding (both before and after the service), indicating that more religiously engaged individuals tend to enter and leave rituals with stronger feelings of connection to their congregation. This pattern is in line with longitudinal evidence that regular religious behaviours and embeddedness in religious communities are associated with richer religious social support networks and better mental health outcomes, partly because religious involvement provides repeated opportunities to build and maintain supportive ties [102,103]. Together, these findings imply that rituals may operate on two timescales: acutely, by temporarily boosting bonding via mu-opioid-linked and affective processes in any given service, and chronically, by contributing over months and years to elevated baseline social bonding among more religiously committed congregants.

Moreover, we found that the role of positive affect in predicting social bonding differed between the UK and Brazil. In Brazil, higher positive affect was less predictive of social bonding than it was in the UK participants. In addition, the change in positive affect from before to after the ritual was not statistically significant in Brazil after correcting for multiple tests, and a likely reason for this is a pre-ritual ceiling effect on positive affect among Brazilian participants. One interpretation is that, in the Brazilian context, high levels of positive affect during ritual may be relatively normative and therefore less informative about changes in perceived closeness, perhaps because cultural norms place a stronger emphasis on warm, expressive interpersonal styles and on maintaining positive social harmony [104]. By contrast, in the UK congregations, where emotional restraint and concerns about exuberant expression may be more salient, moments of heightened positive affect during ritual may stand out more clearly as signals of social connection and shared experience, making individual differences in positive affect more predictive of perceived bonding.

One possible limitation of the current study is that participants were recruited from two culturally distinct countries in uneven numbers. In part, this was the result of a higher average number of participants who met at least one exclusion criterion in the UK as compared to Brazil (possibly due to a higher average age): 38% of British participants had to be excluded, in contrast with only 21% of Brazilian participants. This difference in participant numbers meant that exploratory tests comparing UK to Brazilian data were not conducted, as there were not enough participants recruited in the UK to have a well-powered enough analysis to find a significant relationship between social bonding and pain threshold within the group. Another limitation is that, as this is a naturalistic field study, we did not have a control condition in this study. Site selection was also shaped by researchers' access to religious groups in both countries, which is an opportunity bias worth acknowledging alongside the principled sampling rationale.

One pre-registered analysis, quantifying behavioural synchrony during the rituals, could not be carried out due to varying video quality and technical problems. Two further hypotheses, therefore, remain untested: (i) that behavioural synchrony, believed to enhance the release of mu-opioids [33,34], would predict changes in social bonding [105], and (ii) that this would be mediated by change in pain threshold. Directly testing these synchrony-based pathways in naturalistic ritual settings remains an important target for future research.

In conclusion, this field study provides evidence that participation in doctrinal religious rituals is associated with increases in feelings of social bonding from before to after the service. The study also shows that this increase in social bonding is predicted by increases in mu-opioid-linked pain threshold and positive affect and by decreases in negative affect. These findings support the 'brain-opioid theory of social attachment' [1,4] in ecologically valid religious settings and suggest that doctrinal rituals function as scalable cultural practices that repeatedly recruit evolved neurochemical systems for human social bonding.

Ethics. This research was designed in accordance with the regulations of the British Psychological Society and was reviewed and approved by Coventry University Ethics Committee (no. P53423). The privacy rights of human subjects have been observed, and informed consent was obtained for experimentation with human subjects.

Data accessibility. All data, code and materials supporting this article are available on the Open Science Framework at [106].

Supplementary material is available online [107].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. S.J.C.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, writing—original draft, writing—review and editing; V.v.M.: investigation, methodology, project administration, supervision, validation, visualization, writing—review and editing; R.Du.: conceptualization, funding acquisition, methodology, project administration, supervision, writing—review and editing; J.E.B.: investigation, writing—review and editing; R.De.: investigation; E.M.: investigation, writing—review and editing; L.T.: conceptualization, funding acquisition, writing—review and editing; F.W.: conceptualization, funding acquisition, methodology, project administration, resources, writing—review and editing; J.W.: conceptualization, methodology, writing—review and editing; M.F.: conceptualization, funding acquisition, methodology, supervision, writing—review and editing.

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References

1. Machin AJ, Dunbar RIM. 2011 The brain opioid theory of social attachment: a review of the evidence. *Behaviour* **148**, 985–1025. (doi:10.1163/000579511X596624)
2. Nummenmaa L *et al*. 2016 Social touch modulates endogenous μ-opioid system activity in humans. *Neuroimage* **138**, 242–247. (doi:10.1016/j.neuroimage.2016.05.063)
3. Dunbar RIM. 2017 What's missing from the scientific study of religion? *Religion. Brain Behav.* **7**, 349–353. (doi:10.1080/2153599X.2016.1249927)
4. Panksepp J, Herman B, Conner R, Bishop P, Scott JP. 1978 The biology of social attachments: opiates alleviate separation distress. *Biol. Psychiatry Cogn. Neurosci. Neuroimaging* **13**, 607–618.
5. Panksepp J, Herman BH, Vilberg T, Bishop P, DeEskinazi FG. 1980 Endogenous opioids and social behavior. *Neurosci. Biobehav. Rev.* **4**, 473–487. (doi:10.1016/0149-7634(80)90036-6)
6. Burkett JP, Spiegel LL, Inoue K, Murphy AZ, Young LJ. 2011 Activation of μ-opioid receptors in the dorsal striatum is necessary for adult social attachment in monogamous prairie voles. *Neuropsychopharmacology* **36**, 2200–2210. (doi:10.1038/npp.2011.117)
7. Kobayashi T, Kiyokawa Y, Arata S, Takeuchi Y, Mori Y. 2013 Naloxone blocks the deterioration of male sexual behavior induced by alarm pheromone in rats. *J. Vet. Med. Sci.* **75**, 761–765. (doi:10.1292/jvms.12-0454)
8. Resendez SL, Dome M, Gormley G, Franco D, Nevárez N, Hamid AA, Aragona BJ. 2013 μ-Opioid receptors within subregions of the striatum mediate pair bond formation through parallel yet distinct reward mechanisms. *J. Neurosci.* **33**, 9140–9149. (doi:10.1523/JNEUROSCI.4123-12.2013)
9. Inagaki TK, Hazlett LI, Andreescu C. 2019 Naltrexone alters responses to social and physical warmth: implications for social bonding. *Soc. Cogn. Affect. Neurosci.* **14**, 471–479. (doi:10.1093/scan/nsz026)
10. Loseth GE, Ellingsen DM, Leknes S. 2014 State-dependent μ-opioid modulation of social motivation. *Front. Behav. Neurosci.* **8**, 430. (doi:10.3389/fnbeh.2014.00430)
11. Bamford J, Burger B, Toiviainen P. 2016 Are we dancing to the same beat? Empathy and interpersonal synchronisation in the silent disco. In *9th International Conference of Students of Systematic Musicology (SysMus 16)*. Jyväskylä, Finland: University of Jyväskylä.
12. Cross L, Turgeon M, Atherton G. 2019 Moving with the in-crowd: cooperation and interpersonal entrainment in in-vs. out-groups. *Current Psychology* **40**, 3393–3400. (doi:10.1007/s12144-019-00283-0)
13. Pearce E, Wlodarski R, Machin AJ, Dunbar RIM. 2017 Variation in the β-endorphin, oxytocin, and dopamine receptor genes is associated with different dimensions of human sociality. *Proc. Natl Acad. Sci. USA* **114**, 5300–5305. (doi:10.1073/pnas.1700712114)
14. Tarr B, Launay J, Cohen E, Dunbar RIM. 2015 Synchrony and exertion during dance independently raise pain threshold and encourage social bonding. *Biol. Lett.* **11**, 20150767. (doi:10.1098/rsbl.2015.0767)
15. Tarr B, Slater M, Cohen E. 2018 Synchrony and social connection in immersive virtual reality. *Sci. Rep.* **8**, 3693. (doi:10.1038/s41598-018-21765-4)
16. Wilson S, Gos C. 2019 Perceiving social cohesion: Movement synchrony and task demands both matter. *Perception* **48**, 316–329. (doi:10.1177/0301006619837878)
17. Wiltermuth SS, Heath C. 2009 Synchrony and cooperation. *Psychol. Sci.* **20**, 1–5. (doi:10.1111/j.1467-9280.2008.02253.x)
18. Jaremka LM, Sunami N, Nadzan MA. 2017 Eating moderates the link between body mass index and perceived social connection. *Appetite* **112**, 124–132. (doi:10.1016/j.appet.2017.01.016)
19. Sayette MA, Creswell KG, Dimoff JD, Fairbairn CE, Cohn JF, Heckman BW, Kirchner TR, Levine JM, Moreland RL. 2012 Alcohol and group formation: a multimodal investigation of the effects of alcohol on emotion and social bonding. *Psychol. Sci.* **23**, 869–878. (doi:10.1177/0956797611435134)
20. Pearce E, Launay J, Dunbar RIM. 2015 The ice-breaker effect: singing mediates fast social bonding. *R. Soc. Open Sci.* **2**, 150221. (doi:10.1098/rsos.150221)
21. Pearce E, Launay J, van Duijn M, Rotkirch A, David-Barrett T, Dunbar RIM. 2016 Singing together or apart: The effect of competitive and cooperative singing on social bonding within and between sub-groups of a university Fraternity. *Psychol. Music* **44**, 1255–1273. (doi:10.1177/0305735616636208)
22. Reddish P, Fischer R, Bulbulia J. 2013 Let's dance together: synchrony, shared intentionality and cooperation. *PLoS One* **8**, e71182. (doi:10.1371/journal.pone.0071182)
23. Wolf W, Launay J, Dunbar RIM. 2016 Joint attention, shared goals, and social bonding. *Br. J. Psychol.* **107**, 322–337. (doi:10.1111/bjop.12144)
24. Dunbar RIM. 2017 Breaking bread: The functions of social eating. *Adapt. Human Behav. Physiol.* **3**, 198–211. (doi:10.1007/s40750-017-0061-4)
25. Dunbar RIM. 2013 The origin of religion as a small-scale phenomenon. In *Religion, intolerance, and conflict* (eds S Clarke, R Powell, J Savulescu), pp. 48–66. Oxford, UK: Oxford University Press. (doi:10.1093/acprof:oso/9780199640911.003.0003)
26. Fischer R, Xygalatas D. 2014 Extreme rituals as social technologies. *J. Cogn. Cult.* **14**, 345–355. (doi:10.1163/15685373-12342130)
27. Fischer R, Xygalatas D, Mitkidis P, Reddish P, Tok P, Konvalinka I, Bulbulia J. 2014 The fire-walker's high: affect and physiological responses in an extreme collective ritual. *PLoS One* **9**, e88355. (doi:10.1371/journal.pone.0088355)
28. Frecska E, Kulcsar Z. 1989 Social bonding in the modulation of the physiology of ritual trance. *Ethos* **17**, 70–87. (doi:10.1525/eth.1989.17.1.02a00040)
29. Power EA. 2018 Collective ritual and social support networks in rural South India. *Proc. R. Soc. B* **285**, 20180023. (doi:10.1098/rspb.2018.0023)
30. Xygalatas D, Konvalinka I, Bulbulia J, Roepstorff A. 2011 Quantifying collective effervescence: heart-rate dynamics at a fire-walking ritual. *Commun. Integr. Biol.* **4**, 735–738. (doi:10.4161/cib.17609)
31. Konvalinka I, Xygalatas D, Bulbulia J, Schjødt U, Jegindø EM, Wallot S, Van Orden G, Roepstorff A. 2011 Synchronized arousal between performers and related spectators in a fire-walking ritual. *Proc. Natl Acad. Sci. USA* **108**, 8514–8519. (doi:10.1073/pnas.1016955108)
32. Xygalatas D, Mitkidis P, Fischer R, Reddish P, Skewes J, Geertz AW, Roepstorff A, Bulbulia J. 2013 Extreme rituals promote prosociality. *Psychol. Sci.* **24**, 1602–1605. (doi:10.1177/0956797612472910)
33. Cohen EEA, Ejsmond-Frey R, Knight N, Dunbar RIM. 2010 Rowers' high: behavioural synchrony is correlated with elevated pain thresholds. *Biol. Lett.* **6**, 106–108. (doi:10.1098/rsbl.2009.0670)
34. Launay J, Tarr B, Dunbar RIM. 2016 Synchrony as an adaptive mechanism for large-scale human social bonding. *Ethology* **122**, 779–789. (doi:10.1111/eth.12528)
35. van Mulukom V, Clark R, Eikelboom L, Newheiser D, Joseph J, Farias M. 2025 *Blurring of self-other boundaries is associated with awe and social bonding in an art ritual performance*. PsyArXiv. See https://doi.org/10.31234/osf.io/6atkp_v2.
36. Van Mulukom V, Lang M. 2021 Religious experiences are interpreted through priors from cultural frameworks supported by imaginative capacity rather than special cognition. *JCSR* **7**, 39–53. (doi:10.1558/jcsr.19803)

37. Whitehouse H. 2004 *Modes of religiosity: a cognitive theory of religious transmission*. Walnut Creek, CA: Altamira.
38. van Mulukom V. 2017 Remembering religious rituals: autobiographical memories of high-arousal religious rituals considered from a narrative processing perspective. *Religion. Brain Behav.* **7**, 191–205. (doi:10.1080/2153599X.2016.1232304)
39. Fischer R, Kruekaew J. 2020 Synchrony vs. pain in males and females: an examination of differential effects on social bonding in a naturally occurring ritual. *Religion. Brain Behav.* **10**, 407–427. (doi:10.1080/2153599X.2019.1626271)
40. Gangestad SW, Grebe NM. 2017 Hormonal systems, human social bonding, and affiliation. *Horm. Behav.* **91**, 122–135. (doi:10.1016/j.yhbeh.2016.08.005)
41. Witt KA, Davis TP. 2006 CNS drug delivery: opioid peptides and the blood-brain barrier. *AAPS J.* **8**, E76–88. (doi:10.1208/aapsj080109)
42. Zubieta JK, Ketter TA, Bueller JA, Xu Y, Kilbourn MR, Young EA, Koeppe RA. 2003 Regulation of human affective responses by anterior cingulate and limbic mu-opioid neurotransmission. *Arch. Gen. Psychiatry* **60**, 1145–1153. (doi:10.1001/archpsyc.60.11.1145)
43. Zubieta JK, Smith YR, Bueller JA, Xu Y, Kilbourn MR, Jewett DM, Meyer CR, Koeppe RA, Stohler CS. 2001 Regional mu opioid receptor regulation of sensory and affective dimensions of pain. *Science* **293**, 311–315. (doi:10.1126/science.1060952)
44. Tarr B, Launay J, Dunbar RIM. 2016 Silent disco: dancing in synchrony leads to elevated pain thresholds and social closeness. *Evol. Hum. Behav.* **37**, 343–349. (doi:10.1016/j.evolhumbehav.2016.02.004)
45. Rhudy JL, Meagher MW. 2001 The role of emotion in pain modulation. *Curr. Opin. Psychiatry* **14**, 241–245. (doi:10.1097/00001504-200105000-00012)
46. Nummenmaa L, Tuominen L. 2018 Opioid system and human emotions. *Br. J. Pharmacol.* **175**, 2737–2749. (doi:10.1111/bph.13812)
47. Fredrickson BL. 2013 Positive emotions broaden and build. *Adv. Exp. Social Psychol* **47**, 1–53. (doi:10.1016/B978-0-12-407236-7.00001-2)
48. Henrich J, Heine SJ, Norenzayan A. 2010 Most people are not WEIRD. *Nature* **466**, 29–29. (doi:10.1038/466029a)
49. Bakermans-Kranenburg MJ, van Ijzendoorn MH. 2014 A sociability gene? Meta-analysis of oxytocin receptor genotype effects in humans. *Psychiatr. Genet.* **24**, 45–51. (doi:10.1097/YPG.0b013e3283643684)
50. Newson M, Buhrmester M, Xygalatas D, Whitehouse H. 2019 Go WILD, Not WEIRD. *J. Cogn. Sci. Relig* **5**, 1–27. (doi:10.1558/jcsr.38413)
51. Savage PE *et al*. 2025 Does synchronised singing enhance social bonding more than speaking does? A global experimental Stage 1 Registered Report. (doi:10.31234/osf.io/pv3m9)
52. Wessel J. 1995 The reliability and validity of pain threshold measurements in osteoarthritis of the knee. *Scand. J. Rheumatol.* **24**, 238–242. (doi:10.3109/03009749509100881)
53. Themistocleous AC, Ramirez JD, Shillo PR, Lees JG, Selvarajah D, Orengo C, Tesfaye S, Rice ASC, Bennett DLH. 2016 The Pain in Neuropathy Study (PiNS): a cross-sectional observational study determining the somatosensory phenotype of painful and painless diabetic neuropathy. *Pain* **157**, 1132–1145. (doi:10.1097/j.pain.0000000000000491)
54. Stickley A, Koyanagi A, Takahashi H, Kamio Y. 2016 ADHD symptoms and pain among adults in England. *Psychiatry Res.* **246**, 326–331. (doi:10.1016/j.psychres.2016.10.004)
55. Goland RS, Wardlaw SL, Stark RI, Frantz AG. 1981 Human plasma β-endorphin during pregnancy, labor, and delivery. *J. Clin. Endocrinol. Metab.* **52**, 74–78. (doi:10.1210/jcem-52-1-74)
56. Thompson T, Oram C, Correll CU, Tsermentseli S, Stubbs B. 2017 Analgesic effects of alcohol: a systematic review and meta-analysis of controlled experimental studies in healthy participants. *J. Pain* **18**, 499–510. (doi:10.1016/j.jpain.2016.11.009)
57. Faul F, Erdfelder E, Lang AG, Buchner A. 2007 G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* **39**, 175–191. (doi:10.3758/bf03193146)
58. Snijders TA. 2005 Power and sample size in multilevel linear models. In *Encyclopedia of statistics in behavioral science* (eds BS Everitt, DC Howell). Chichester, UK: Wiley. (doi:10.1002/0470013192)
59. Delmonte R, Farias M, Bastos MAV Júnior, Madeira L, Sonego B. 2022 The mind possessed: well-being, personality, and cognitive characteristics of individuals regularly experiencing religious possession. *Braz. J Psychiatry* **44**, 486–494. (doi:10.47626/1516-4446-2021-2414)
60. Engler S. 2017 Umbanda. In *Handbook of contemporary religions in Brazil* (eds B Schmidt, S Engler), pp. 204–224. Leiden, The Netherlands: Brill. (doi:10.1163/9789004322134_013)
61. Espírito Santo D. 2017 Possession consciousness, religious individualism, and subjectivity in Brazilian Umbanda. *Religion* **47**, 179–202. (doi:10.1080/0048721X.2016.1198839)
62. Hove MJ, Risen JL. 2009 It's all in the timing: Interpersonal synchrony increases affiliation. *Soc. Cogn.* **27**, 949–960. (doi:10.1521/soco.2009.27.6.949)
63. Valdesolo P, Desteno D. 2011 Synchrony and the social tuning of compassion. *Emotion* **11**, 262–266. (doi:10.1037/a0021302)
64. Aron A, Aron EN, Smollan D. 1992 Inclusion of other in the self scale and the structure of interpersonal closeness. *J. Pers. Soc. Psychol.* **63**, 596–612. (doi:10.1037/0022-3514.63.4.596)
65. Dunbar RIM *et al*. 2012 Social laughter is correlated with an elevated pain threshold. *Proc. R. Soc. B* **279**, 1161–1167. (doi:10.1098/rspb.2011.1373)
66. Dunbar RIM, Kaskatis K, MacDonald I, Barra V. 2012 Performance of music elevates pain threshold and positive affect: implications for the evolutionary function of music. *Evol. Psychol.* **10**, 688–702. (doi:10.1177/147470491201000403)
67. Graven-Nielsen T, Vaegter HB, Finocchietti S, Handberg G, Arendt-Nielsen L. 2015 Assessment of musculoskeletal pain sensitivity and temporal summation by cuff pressure algometry: a reliability study. *Pain* **156**, 2193–2202. (doi:10.1097/j.pain.0000000000000294)
68. Jones DH, Kilgour RD, Comtois AS. 2007 Test-retest reliability of pressure pain threshold measurements of the upper limb and torso in young healthy women. *J. Pain* **8**, 650–656. (doi:10.1016/j.jpain.2007.04.003)
69. Bruehl S, Chung OY, Chont M. 2010 Chronic pain-related changes in endogenous opioid analgesia: a case report. *Pain* **148**, 167–171. (doi:10.1016/j.pain.2009.09.025)
70. Schobel HP, Handwerker HO, Schmieder RE, Heusser K, Dominiak P, Luft FC. 1998 Effects of naloxone on hemodynamic and sympathetic nerve responses to pain in normotensive vs. borderline hypertensive men. *J. Auton. Nerv. Syst.* **69**, 49–55. (doi:10.1016/s0165-1838(98)00005-8)
71. Hagelberg N, Aalto S, Tuominen L, Pesonen U, Någren K, Hietala J, Scheinin H, Pertovaara A, Martikainen IK. 2012 Striatal μ-opioid receptor availability predicts cold pressor pain threshold in healthy human subjects. *Neurosci. Lett.* **521**, 11–14. (doi:10.1016/j.neulet.2012.05.042)
72. Huang CJ, Liu HF, Su NY, Hsu YW, Yang CH, Chen CC, Tsai PS. 2008 Association between human opioid receptor genes polymorphisms and pressure pain sensitivity in females. *Anaesthesia* **63**, 1288–1295. (doi:10.1111/j.1365-2044.2008.05760.x)
73. Watson D, Clark LA, Tellegen A. 1988 Development and validation of brief measures of positive and negative affect: the PANAS scales. *J. Pers. Soc. Psychol.* **54**, 1063–1070. (doi:10.1037//0022-3514.54.6.1063)
74. Koenig HG, Büssing A. 2010 The Duke University Religion Index (DUREL): a five-item measure for use in epidemological studies. *Religions (Basel)* **1**, 78–85. (doi:10.3390/rel1010078)
75. Dobrowolska B, Jurek K, Pilewska-Kozak AB, Pawlikowski J, Drozd M, Koenig H. 2016 Validation of the polish version of the Duke University Religion Index (PolDUREL). *Pol. Arch. Med. Wewn.* **126**, 1005–1008. (doi:10.20452/pamw.3721)

76. Lucchetti G, Granero Lucchetti AL, Peres MF, Leão FC, Moreira-Almeida A, Koenig HG. 2012 Validation of the Duke Religion Index: Durel (Portuguese version). *J. Relig. Health* **51**, 579–586. (doi:10.1007/s10943-010-9429-5)
77. de Paula JJ. 2015 Propriedades psicométricas do índice de religiosidade de duke aplicado em plataforma virtual. *Cad. Saúde Colet.* **23**, 276–279. (doi:10.1590/1414-462X201500030090)
78. Brown JE, van Mulukom V, Charles SJ, Farias M. Do you need religion to enjoy the benefits of Church services? Social bonding, morality and quality of life among religious and secular congregations. *Psycholog. Relig. Spiritual.* **15**, 308–318. (doi:10.1037/rel0000447)
79. R Core Team. 2020 *R: a language and environment for statistical computing*. R Foundation for Statistical Computing. See https://www.R-project.org.
80. Fillingim RB. 2017 Sex, gender, and pain. In *Principles of gender-specific medicine* (ed. MJ Legato), pp. 481–496. New York, NY: Academic Press. (doi:10.1016/B978-0-12-803506-1.00038-3)
81. Lumley MA, Cohen JL, Borszcz GS, Cano A, Radcliffe AM, Porter LS, Schubiner H, Keefe FJ. 2011 Pain and emotion: a biopsychosocial review of recent research. *J. Clin. Psychol.* **67**, 942–968. (doi:10.1002/jclp.20816)
82. Aho K, Derryberry D, Peterson T. 2014 Model selection for ecologists: the worldviews of AIC and BIC. *Ecology* **95**, 631–636. (doi:10.1890/13-1452.1)
83. Luke SG. 2017 Evaluating significance in linear mixed-effects models in R. *Behav. Res. Methods* **49**, 1494–1502. (doi:10.3758/s13428-016-0809-y)
84. Akaike H. 1973 Maximum likelihood identification of Gaussian autoregressive moving average models. *Biometrika* **60**, 255–265. (doi:10.1093/biomet/60.2.255)
85. Satterthwaite FE. 1941 Synthesis of variance. *Psychometrika* **6**, 309–316. (doi:10.1007/BF02288586)
86. Fredrickson BL. 2001 The role of positive emotions in positive psychology: the broaden-and-build theory of positive emotions. *Am. Psychol.* **56**, 218–226. (doi:10.1037//0003-066x.56.3.218)
87. Kosfeld M, Heinrichs M, Zak PJ, Fischbacher U, Fehr E. 2005 Oxytocin increases trust in humans. *Nature New Biol.* **435**, 673–676. (doi:10.1038/nature03701)
88. Nave G, Camerer C, McCullough M. 2015 Does oxytocin increase trust in humans? A critical review of research. *Perspect. Psychol. Sci.* **10**, 772–789. (doi:10.1177/1745691615600138)
89. Bartz JA, Zaki J, Bolger N, Ochsner KN. 2011 Social effects of oxytocin in humans: context and person matter. *Trends Cogn. Sci. (Regul. Ed.)* **15**, 301–309. (doi:10.1016/j.tics.2011.05.002)
90. Bethlehem RAI, Baron-Cohen S, van Honk J, Auyeung B, Bos PA. 2014 The oxytocin paradox. *Front. Behav. Neurosci.* **8**, 48. (doi:10.3389/fnbeh.2014.00048)
91. Bos PA, Panksepp J, Bluthé RM, van Honk J. 2012 Acute effects of steroid hormones and neuropeptides on human social-emotional behavior: a review of single administration studies. *Front. Neuroendocrinol.* **33**, 17–35. (doi:10.1016/j.yfrne.2011.01.002)
92. Van Cappellen P, Toth-Gauthier M, Saroglou V, Fredrickson BL. 2016 Religion and well-being: the mediating role of positive emotions. *J. Happiness Stud.* **17**, 485–505. (doi:10.1007/s10902-014-9605-5)
93. Inagaki TK, Ray LA, Irwin MR, Way BM, Eisenberger NI. 2016 Opioids and social bonding: naltrexone reduces feelings of social connection. *Soc. Cogn. Affect. Neurosci.* **11**, 728–735. (doi:10.1093/scan/nsw006)
94. Charles SJ, Farias M, van Mulukom V, Saraswati A, Dein S, Watts F, Dunbar RIM. 2020 Blocking mu-opioid receptors inhibits social bonding in rituals. *Biol. Lett.* **16**, 20200485. (doi:10.1098/rsbl.2020.0485)
95. Werner MU, Pereira MP, Andersen LPH, Dahl JB. 2015 Endogenous opioid antagonism in physiological experimental pain models: a systematic review. *PLoS ONE* **10**, e0125887. (doi:10.1371/journal.pone.0125887)
96. Atwood S, Schachner A, Mehr SA. 2022 Expectancy effects threaten the inferential validity of synchrony-prosociality research. *Open Mind* **6**, 280–290. (doi:10.1162/opmi_a_00067)
97. Tunçgenç B, Bamford JS, Fawcett C, Cohen E. 2023 The synchrony-prosociality link cannot be explained away as expectancy effect: response to Atwood et al. *Open Mind (Camb)* **7**, 711–714. (doi:10.1162/opmi_a_00103)
98. Rennung M, Göritz AS. 2016 Prosocial consequences of interpersonal synchrony: a meta-analysis. *Z. Psychol.* **224**, 168–189. (doi:10.1027/2151-2604/a000252)
99. Mehr SA, Krasnow MM, Bryant GA, Hagen EH. 2021 Origins of music in credible signaling. *Behav. Brain Sci.* **44**, e60. (doi:10.1017/S0140525X20000345)
100. Savage PE, Loui P, Tarr B, Schachner A, Glowacki L, Mithen S, Fitch WT. 2021 Music as a coevolved system for social bonding. *Behav. Brain Sci.* **44**, e59. (doi:10.1017/S0140525X20000333)
101. Dunbar RIM. 2010 The social role of touch in humans and primates: behavioural function and neurobiological mechanisms. *Neurosci. Biobehav. Rev.* **34**, 260–268. (doi:10.1016/j.neubiorev.2008.07.001)
102. Holt CL, Roth DL, Huang J, Clark EM. 2018 Role of religious social support in longitudinal relationships between religiosity and health-related outcomes in African Americans. *J. Behav. Med.* **41**, 62–73. (doi:10.1007/s10865-017-9877-4)
103. Le D, Holt CL, Hosack DP, Huang J, Clark EM. 2016 Religious participation is associated with increases in religious social support in a national longitudinal study of African Americans. *J. Relig. Health* **55**, 1449–1460. (doi:10.1007/s10943-015-0143-1)
104. Fonseca RG, Marques PIS, Costa FF da, Landeira-Fernandez J, Rimes KA, Mograbi DC. 2023 Cross-cultural differences in beliefs about emotions: a comparison between Brazilian and British participants. *J. Bras. Psiquiatr.* **72**, 152–158. (doi:10.1590/0047-2085000000423)
105. Lang M, Bahna V, Shaver JH, Reddish P, Xygalatas D. 2017 Sync to link: endorphin-mediated synchrony effects on cooperation. *Biol. Psychol.* **127**, 191–197. (doi:10.1016/j.biopsycho.2017.06.001)
106. Charles SJ, van Mulukom V, Farias M, Brown J, Dunbar RIM. 2026 RSB1 pre-registration information and data files (doi:10.17605/OSF.IO/WAM9Z)
107. Charles SJ *et al*. 2026 Supplementary material from: Religious rituals in the United Kingdom and Brazil are associated with increased social bonding and pain threshold. Figshare. (doi:10.6084/m9.figshare.c.8528663)