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Neural underpinning of a personal relationship with God and sense of control: A lesion-mapping study

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Abstract

A strong personal relationship with God is theoretically and empirically associated with an enhanced sense of control. While a growing body of research is focused on understanding the neural mechanisms underlying religious belief, little is known about the brain basis of the link between a personal relationship with God and sense of control. Here, we used a sample of patients with focal brain lesions (N = 84) and matched healthy controls (N = 22) to determine whether damage to the ventromedial prefrontal cortex (vmPFC)—a region associated with emotionally meaningful religious experiences and with sense of control—will modulate self-reports of a personal relationship with God and sense of control. We also examined potential mediators for these associations. Voxel-based lesion symptom mapping revealed that damage to the right vmPFC resulted in a stronger personal relationship with God, and patients with damage to this region demonstrated an increased sense of control relative to patients with damage to posterior cortex and healthy controls. Moreover, the association between vmPFC damage and greater perceived sense of control was mediated by a stronger personal relationship with God. Collectively, these results suggest that a strong personal relationship with God can serve an important psychological function by affecting sense of control, with both enhanced following damage to the right vmPFC.

Keywords Ventromedial prefrontal cortex · Personal relationship with God · Sense of control · Voxel-based lesion-symptom mapping

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Introduction

Archeological and cross-cultural evidence indicate that human societies have long been infused with belief in supernatural powers (Watts et al., 2015). Given the prevalence and ancient origins of this unique human belief, understanding its psychological underpinnings in the brain is a fundamental scientific question, and research in cognitive and social psychology has highlighted the importance of the affective components of such beliefs (Gibson, 2008; Schjoedt, Stødkilde-Jørgensen, Geertz, Lund, & Roepstorff, 2010; Schjoedt, Stødkilde-Jørgensen, Geertz, & Roepstorff, 2009).

The legacy of psychological interest in the affective personal qualities of beliefs can be traced to early 20th century psychology. As early as 1902, William James defined religion as "*the feeling, acts and experiences of individual men in their solitude… in relation to whatever they may consider the divine"* (James, 1902, p. 36). More recent work suggests that a personal relationship with God may form the basis for establishing coping strategies in general and forming a sense of control in particular (Fiori, Brown, Cortina, & Antonucci, 2006; Pargament, 2001; Park, 2005; Wong-Mcdonald & Gorsuch, 2000). This argument has found increasing empirical support (Ellison & Burdette, 2012; Kay, Gaucher, Napier, Callan, & Laurin, 2008; Kay, Shepherd, Blatz, Chua, & Galinsky, 2010; Laurin, Kay, & Moscovitch, 2008; Newton & McIntosh, 2010), indicating that a meaningful personal relationship with God helps people maintain a sense of control and stability.

Given the association between a personal relationship with God and sense of control at the behavioral level, one could predict that they both share similar mechanisms at the neuronal level as well; however, no studies have examined this hypothesis directly.

One brain region that may be a key structure in this regard is the ventromedial prefrontal cortex (vmPFC). The vmPFC is traditionally linked to generating affective meaning and emotional valuation (Henri-Bhargava, Simioni, & Fellows, 2012; Hiser & Koenigs, 2018; Roy, Shohamy, & Wager, 2012; Winecoff et al., 2013). Specifically, it was found to play a critical role in belief systems in general (Harris, Sheth, & Cohen, 2008) and religious beliefs and experience in particular. For example, a recent imaging study reported that brain activation in the vmPFC among other brain areas was observed while devout Mormons reported "feeling the Spirit" of the divine (Ferguson et al., 2018). In addition, lesions in the vmPFC were found to associate with greater religious fundamentalism (Asp, Ramchandran, & Tranel, 2012; Zhong, Cristofori, Bulbulia, Krueger, & Grafman, 2017).

Moreover, in a parallel set of studies, the vmPFC also was linked to the ability to evaluate the environment as being controllable or not, both in animals (Amat, Paul, Watkins, & Maier, 2008; Baratta, Lucero, Amat, Watkins, & Maier, 2008) and humans (Bryant, Felmingham, Das, & Malhi, 2014).

In summary, the vmPFC has been shown to play a role in response to emotionally meaningful religious experiences as well as in response to conditions that signify a relative sense of control. Building on these previous findings, the present study explores whether damage to the vmPFC may impact one's personal relationship with God and sense of control and, if so, whether the association with one factor is mediated by the association with the other.

To examine this hypothesis, we collected self-report ratings regarding a personal relationship with God and sense of control from a large group of male veterans with focal brain lesions. While brain-imaging studies using healthy participants can offer correlational insights about brain-behavior relationships, focal lesion studies can provide causal evidence linking a specific brain region with a particular behavioral outcome. We hypothesized that (1) vmPFC brain lesions modulate ratings of one's personal relationship with God; (2) vmPFC brain lesions modulate one's perceived sense of control; and (3) the association between vmPFC damage and perceived sense of control is mediated by a personal relationship with God, and likewise, that the association between vmPFC damage and personal relationship with God is mediated by perceived sense of control.

Materials and methods

Participants

Participants were drawn from Phase 4 of the Vietnam Head Injury Study (VHIS) registry. The VHIS is a long-term study of male combat veterans with focal, penetrating traumatic brain injury (pTBI) and a matched sample of combat veterans who also served in Vietnam but did not sustain brain injuries (Raymont, Salazar, Krueger, & Grafman, 2011). Our group has previously published data on the neural basis of mystical experiences (Cristofori et al., 2016) and religious fundamentalism (Zhong et al., 2017) based on this registry.

In total, 84 participants with pTBI (see Fig. 1A for a lesion overlay) and 22 control participants completed both the personal relationship with God and sense of control scales and were included in the present study. When asked, "Do you believe in God?" the majority of participants in both groups responded "Yes" (74/84 TBI patients and 16/22 controls, $\chi^2(1) = 3.21$, $p = 0.073$). Next, participants responded to a question about their religious affiliation. The pTBI group consisted of 49 Protestants, 24 Roman Catholics, and 3 Mormons. Six participants had other or no affiliation, and two did not respond to this question. The HC group consisted of nine Protestants and eight Roman Catholics. Four participants had other or no affiliation, and one did not respond to this

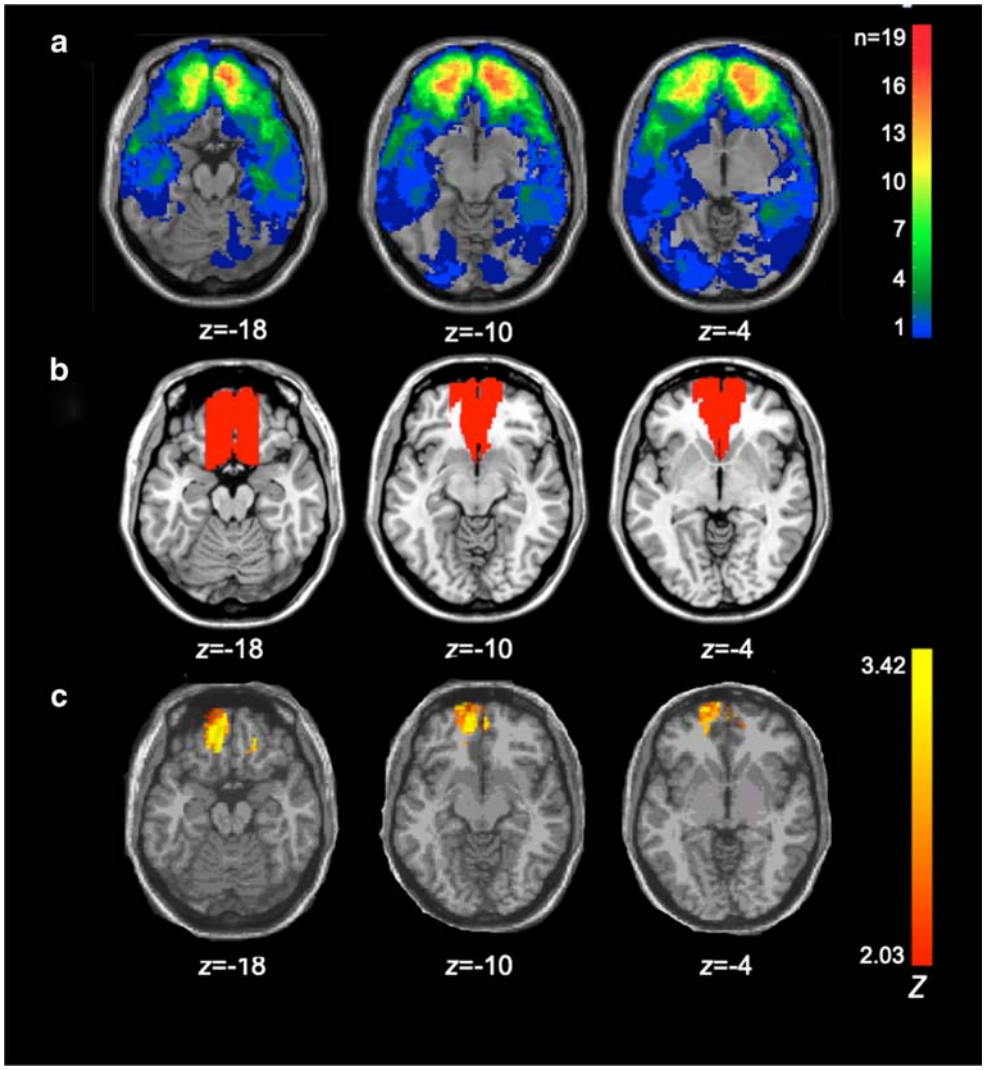

Fig. 1 A. Overlay density map of 84 pTBI patients. Brain regions included in the mask were damaged in a significant number of patients (the color legend indicates number of patients with damage to a particular voxel). **B.** vmPFC mask used to define the ROIs for the VLSM analysis. **C.** VLSM results: damage to a cluster in vmPFC (Table 1) was associated with stronger personal relationship with God. Images are in radiological space (i.e., right is left)

question. Study participants gave their written, informed consent, as approved by an Institutional Review Board at the National Institute of Neurological Disorders and Stroke at the National Institute of Health, Bethesda, MD, USA.

Behavioral procedures

Personal relationship with God scale

Participants' personal relationship with God was assessed using a novel 17-item self-report scale (see Appendix), which was administered during Phase 4 of the VHIS (2008-2012; 40-44 years post injury). The first 11 items in this scale were chosen from the *Presence and Salience* subscales of the God-Image Inventory (Lawrence, 1997; e.g., "I can talk to God on an intimate basis"). Three additional items were added to assess meaningful communication with God (items 12-14; e.g., "God tells me what He wants from me"), and three more items were added to assess communication through a religious experience (items 15-17; e.g., "I find a precise meaning was communicated to me through my religious experience"). Participants responded to items 1-14 on a Likert scale, ranging from 1 (strongly disagree) to 4 (strongly agree), and to items 15-17 on a similarly anchored scale, ranging from 1 to 7. A summed score was calculated for each participant; a higher score indicated a stronger, more meaningful communication and relationship with God. The mean score was 48.54 (standard deviation [SD] = 17.72), and overall scores ranged between 14 and 77. Cronbach's alpha for this scale was 0.94, indicating that the scale has high internal consistency. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.91, and Bartlett's test of sphericity was significant

($x^2(136) = 894.92$, $p < 0.0001$), indicating that the sample could be factored. Exploratory factor analysis with principal component analysis was used, and only one component with eigenvalues greater than 1 was extracted, supporting the use of the scale as a single factor.

Sense of control

A subjective sense of control was assessed based on responses to the question, "How often do you feel powerless to get what you want out of life?" This single item was included in an interview conducted during phase 3 of the VHIS (2003-2006). Responses for the sense of control item were recorded on a 7-point Likert scale ranging from 1 (Never) to 7 (Always, all intermediate points were labeled). The overall median of the scale was 3 (Rarely), the mean was 3.31 and the SD = 1.42. A higher score reflected lower sense of personal control.

Other neuropsychological measures

General intelligence was assessed using the Armed Forces Qualification Test (AFQT-7A; DoD, 1960), which was administered to individuals upon enlistment to the military (preinjury) and later again in each phase of the Vietnam Head Injury Study. This test has been standardized within the U.S. military and correlates highly with Wechsler Adult Intelligence Test scores (Cohen-Zimerman, Salvi, Krueger, Gordon, & Grafman, 2018; Grafman et al., 1988).

Moreover, during Phase 4 of the VHIS, participants underwent extensive neuropsychological testing over a period of 5 days at the National Institute of Neurological Disorders and Stroke. We report a subset of these neuropsychological measures, including the Delis-Kaplan Executive Function System sorting test (D-KEFS; Delis, Kaplan, & Kramer, 2001) for Cognitive flexibility and the Openness dimension of the revised NEO Personality Inventory (NEO-PI-R; Costa & Mac Crae, 1992) for an open personality.

We also report ratings of political orientation (self-reported item, 7-point scale ranging from 1 = liberal to 7 = conservative), affective theory of mind (Faux Pas Recognition task; Stone, Baron-Cohen, & Knight, 1998), depression (Beck Depression Inventory-II; Beck, Steer, & Brown, 1996), and posttraumatic stress disorder (Mississippi Post Traumatic Stress Disorder scale; Keane, Caddell, & Taylor, 1988).

Lesion-symptom mapping procedures

Computed tomography scans and lesion localization

The axial computed tomography (CT) scans used in our analyses were acquired during Phase 3 (2003-2006) of the VHIS. While more recent CT scans were completed at Phase 4 (2008-2012) for clinical purposes, an NIH staff radiologist who viewed them reported no new lesions or significant pathological changes compared to Phase 3. Scans were acquired on GE Medical Systems Light Speed Plus CT scanner at the Bethesda Naval Hospital, Bethesda, MD, USA. We could not use MRI due to the presence of retained metal fragments from penetrating metal objects (e.g., missile fragments or gunshots) and the possible presence of metallic surgical clips or cranioplasties. Helical CT scans were acquired without contrast with a voxel size of 0.4 mm^3, an overlapping slice thickness of 2.5 mm and a 1-mm slice interval. We determined lesion volume by manually tracing the lesion in all relevant slices of the CT image in native space, summing the traced areas, and then multiplying by slice thickness. Lesion tracing was performed by a trained neuropsychiatrist, and reviewed by J.G., who was blind to the patient's experimental or neuropsychological tests results. The CT image of each individual's brain was normalized to a CT template brain image in Montreal Neurological Institute (MNI) space. Afterwards, lesion location and volume were determined using the ABLe software package (Solomon, Raymont, Braun, Butman, & Grafman, 2007) in MEDx v.3.44 environment (Medical Numerics Germantown, MD), with enhancements to support the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002).

Voxel-based lesion-symptom mapping analysis

We preformed VLSM analysis with the goal to identify brain regions that play a causal role in modulating personal relationship with God (Bates et al., 2003). Given our hypothesis-driven approach, we chose to focus our voxel-based lesion-symptom mapping (VLSM) analysis on the vmPFC region of interest (ROI). Specifically, the vmPFC ROI contained regions of the PFC inferior to the anterior commissure ($z < 0$) and within 20 mm ($-20 < x < 20$). This ROI spanned several AAL regions, including superior frontal gyrus (medial, orbital, and medial orbital parts), middle frontal gyrus (orbital), inferior frontal gyrus (orbital), gyrus rectus, olfactory cortex, anterior cingulate cortex, and the paracingulate gyri (Hogeveen, Hauner, Chau, Krueger, & Grafman, 2017; Koenigs et al., 2008; Krueger et al., 2009; Fig. 1B). To ensure that we did not miss important results outside the vmPFC ROI, we repeated our VLSM analysis using no mask (i.e., whole brain analysis). Patients' personal relationship with God ratings were normally distributed (Kolmogorov–Smirnov tests: $p = 0.53$); therefore, the VLSM computed *t*-tests contrasting personal relationship with God between patients with and without lesions in a single voxel within the vmPFC ROI mask. We corrected for multiple comparisons by calculating a false discovery rate (FDR) threshold (Benjamini & Hochberg, 1995). Only voxels whose *p*-values survived the FDR threshold at $q = 0.05$ were considered significant, and only voxels damaged in at least four patients were included in the analysis. Lastly, a minimum cluster size

of 50 voxels was required for the cluster to be reported. Brain structures were identified using the AAL atlas (Tzourio-Mazoyer et al., 2002).

Group comparisons

For one set of analyses (see Section 3.4, "Group comparisons"), participants were divided into three groups based on their brain lesion locations. First, given that the findings from the VLSM analysis emphasized the *right* vmPFC, we grouped veterans with lesions in this area, which was defined based on specifying the lower and upper x, y, and z coordinates in MNI space ($0 \leq x \leq 20$, $z \leq 1$). Because small lesion volumes are more likely to result in behavioral recovery, we set a volume threshold (15% volume loss) above which it was more likely that any acquired behavioral changes would still be present at testing (Cohen-Zimerman, Chau, Krueger, Gordon, & Grafman, 2017; Koenigs et al., 2008; Tranel, Damasio, Denburg, & Bechara, 2005). Only patients with 15% or more damage to the right vmPFC were included in this group (*right vmPFC group*, n = 13). Next, we grouped veterans with pTBI and 0% damage to right vmPFC and other PFC regions (*posterior cortex group*, n = 26). Lastly, we grouped veterans with no brain injury (*CTRL*, n = 22). Overlay density maps of the two patient groups confirmed that the posterior group did not have damage to the vmPFC, and the vmPFC group had a relatively preserved posterior cortex (Fig. 2).

Mediation analysis procedure

To test the hypothesis that sense of control is mediating the association between vmPFC lesion and a personal relationship with God, or that a personal relationship with God is mediating the association between vmPFC lesion and sense of control, we performed mediation analyses in all pTBI patients. Given the results from the VLSM analysis emphasizing the *right* vmPFC, we entered right vmPFC lesion size as the independent variable and personal relationship with God score and the sense of control rating as either the mediating or the dependent variable. To compute the percentage of damage to the right vmPFC, the number of lesioned voxels in the right vmPFC ROI was summed and divided by the total number of voxels in the region.

We used the PROCESS v3.1 (Hayes, 2018) macro implemented in SPSS 25.0 (IBM Corporation, Armonk, NY). The TBI patients' data violated the assumption of normality on the sense of control scale (Kolmogorov–Smirnov tests, p = 0.026). Therefore, in our mediation model, we used a bootstrapping approach (5,000 iterations) to compute bias-corrected 95% confidence intervals (CIs) to test for significant indirect effects, a powerful inferential technique that does not assume a normal distribution (Hayes & Scharkow, 2013).

Statistical analysis

We performed all behavioral analysis with SPSS 25.0, with the significance level set to 0.05 (two-tailed). We examined the normality of data using the Kolmogorov-Smirnov test, and nonparametric tests were conducted on nonnormally distributed data. We computed a Spearman rank correlation coefficient to assess the relationship between personal relationship with God and sense of control. Next, we compared personal relationship with God scores across the lesion groups using ANOVA and post-hoc t-test with a Bonferroni correction, and sense of control scores using a Kruskal-Wallis test and post-hoc Mann-Whitney U test with a Bonferroni correction. Effect

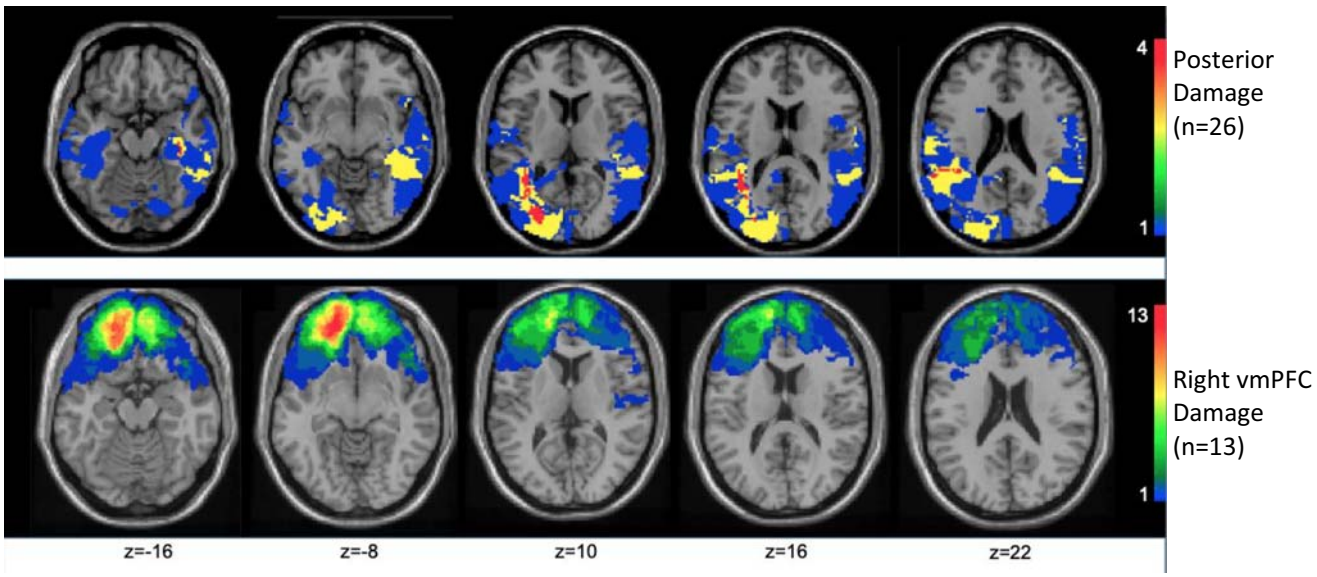

Fig. 2 Group lesion overlay of the two lesion groups [posterior cortex, right vmPFC]. Values below indicate the z coordinates (MNI) of each axial slice. Warmer colors indicate greater lesion overlap (units: number of patients with lesion in this region). Images are in radiological space (i.e., right is left)

sizes were calculated (Cohen's d, d = 0.2 indicates a small effect size, d = 0.5 a medium effect size, and d = 0.8 a large effect size), as well as 95% confidence intervals (CI) for the difference between the means, representing the observed difference between groups. In addition, χ^2 tests and liner regression were performed to compare variables between groups as described in the result section. Finally, we conducted a mediation analysis as described above.

Results

Matching of pTBI and healthy control participants

pTBI and control (CTRL) participants were matched with respect to age (M_{TBI} = 63.33 years, SD_{TBI} = 3.04; M_{CTRL} = 63.77, SD_{CTRL} = 3.84; p = 0.56), handedness (69/84 right-handed TBI patients; 16/22 right-handed controls, $\chi^2(2)$ = 2.35, p = 0.308), and preinjury general intelligence (M_{TBI} = 64.94 percentile, SD_{TBI} = 22.09; M_{CTRL} = 68.77 percentile, SD_{CTRL} = 19.82; p = 0.55). Although the TBI group had lower *post-injury* intelligence (M_{TBI} = 57.02 percentile, SD_{TBI} = 26.08; M_{CTRL} = 70.33 percentile, SD_{CTRL} = 21.77; p = 0.03), both groups performed above the 50th percentile, reflecting performance within the normal range. Moreover, the control group had on average one more year of formal education compared with the TBI group (M_{TBI} = 14.44 years, SD_{TBI} = 2.21; M_{CTRL} = 15.5 years, SD_{CTRL} = 2.01; p = 0.04).

Personal relationship with God scale score

On average, participants in the pTBI group reported *higher* personal relationship with God scores compared with the control group (M_{TBI} = 50.44, SD_{TBI} = 17.12; M_{CTRL} = 41.31, SD_{CTRL} = 18.51; t (104) = 2.18, p = 0.03, CI = 0.85-17.39, Cohen's d = 0.51), reflecting a closer, more meaningful connection with God in the patient's group. As expected, based on previous research (Jackson, Hester, & Gray, 2018; Zhong et al., 2017), higher personal relationship with God scores were correlated with a more conservative political orientation (r = 0.22, p = 0.02), less cognitive flexibility (r = −0.24, p = 0.01), and less open personality (r = −0.21, p = 0.02) across the entire sample. We did not observe a correlation between personal relationship with God score and sense of control ratings in the control group (*rho* = −0.14, p = 0.52) or in the right vmPFC group (*rho* = −0.18, p = 0.53), but among the posterior cortex group, a higher personal relationship with God score correlated with less sense of control (*rho* = 0.57, p = 0.002).

Lastly, within the patient group, higher personal relationship with God scores correlated with a higher percent of total brain volume loss (*rho* = 0.26, p = 0.01) as well as with a higher percent of volume loss in the right (*rho* = 0.22, p = 0.03) and left (*rho* = 0.23, p = 0.03) vmPFC.

Neural underpinning of personal relationship with God: VLSM analysis

We began by performing a whole brain VLSM analysis to examine whether damage in a specific brain area is associated with a higher score on the personal relationship with God scale. At least four patients were required to have damage to a given voxel for that voxel to be considered by the VLSM analysis. This analysis did not yield any significant findings.

Given our hypothesis-driven interest in the vmPFC, we next performed an ROI-based analysis. Such an analysis increases statistical power by reducing the search space from tens of thousands of voxels to just those in a restricted ROI and is therefore more sensitive and often used when an a-priori hypothesis regarding the brain region involved is available (Saxe, Brett, & Kanwisher, 2006). Our next analysis focused on the vmPFC ROI (see Fig. 1B for an image of the vmPFC mask used). An overlay map of the entire patient group demonstrated that much of the masked ROI was damaged in more than four patients (Fig. 1A). This analysis identified a right lateralized cluster within the vmPFC, significantly associated with a higher score in the personal relationship with God scale (Fig. 1C; Table 1).

Given the ROI-based results, we further examined laterality effects within the vmPFC. We conducted a linear regression, with personal relationship with God scores as the dependent variable and the percentage of brain volume loss in the right and left vmPFC as independent variables. The analysis revealed that volume loss to the right vmPFC was a significant predictor of personal relationship with God scores (Beta = 0.27, p = 0.029), whereas left vmPFC was not (Beta = 0.045, p = 0.71). Therefore, in the next set of analyses we focus on the right vmPFC.

Table 1 Results from voxel-based lesion-symptom analyses showing regions of damage associated with higher score in the personal relationship with God scale, see also Figure 1C

Voxels	MNI coordinates			
	x	y	z	z-value
1358	4	58	-14	3.42

Lesion structure	Percentage of volume
Right superior frontal gyrus, orbital part	35.13
Right Middle frontal gyrus, orbital part	4.64
Right Superior frontal gyrus, medial	1.62
Left Superior frontal gyrus, medial orbital	5.52
RIght Superior frontal gyrus, medial orbital	30.93
Left gyrus rectus	1.25
Right gyrus rectus	20.84
Right anterior cingulate gyrus	0.07

Note: MNI coordinates of peak lesion-deficit locations; Regions defined using automated anatomical labeling (AAL)

1.1. Group comparisons

We next sought to find whether groups of patients with different lesion location differ in their personal relationship with God scores. The three groups selected (i.e., right vmPFC lesions, posterior lesions, and healthy controls; see Section 2.4 for details) did not significantly differ with respect to age, handedness, and pre- and post-injury intelligence (all $p \geq 0.31$; Table 2). Given that personal relationship with God ratings were normally distributed in this sample (Kolmogorov–Smirnov test: $p = 0.11$), ANOVA was used to determine a difference between the groups. The overall ANOVA was significant ($F_{2,58} = 4.57$, $p = 0.01$, $\eta^2 = 0.13$; see Table 2), providing evidence that there were group differences in personal relationship with God ratings. Post-hoc tests were computed using the Bonferroni correction test, and the results suggest that a right vmPFC lesion was associated with a significant increase in personal relationship with God ratings relative to the PC group ($p = 0.04$, CI = 0.56- 31.13, Cohen's d = 0.91) and healthy control participants ($p = 0.016$, CI = 2.70-34.19, Cohen's d = 1.09).

Next, we wanted to test whether the three groups differed in their reported sense of control. We ran a Kruskal-Wallis test and again found a significant effect of participant group ($\chi^2 = 6.39$, $p = 0.041$; Table 2). We next contrasted the sense of control in the right vmPFC patients with the other two groups. Post-hoc tests with Bonferroni correction suggested that the right vmPFC group (M = 2.46, SD = 1.26) had a significantly enhanced sense of control relative to the HC group (M = 3.64, SD = 1.46, $p = 0.021$, CI = −2.21 to −0.14, Cohen's d = 0.86) but did not differ from the posterior cortex group (M = 3.27, SD = 0.87, $p = 0.15$, CI = −1.81 to 0.20, Cohen's d = 0.74; Fig. 3).

The group-based analysis therefore suggested that damage to regions of the right vmPFC was associated not only with a stronger personal relationship with God, but also with a greater sense of control compared with healthy controls.

We further examined several variables that have been previously linked to vmPFC functioning and might be expected to covary with personal relationship with God scores, such as empathy (Shamay-Tsoory, 2011), affective theory of mind (Leopold et al., 2012), depression (Koenigs & Grafman, 2009), and posttraumatic stress disorder (Koenigs et al., 2008). None of these variables differed significantly as a function of group (all $p \geq 0.30$; Table 2).

Mediation analysis

Given that both personal relationship with God scores and sense of control were elevated in the right vmPFC group, we next explored the interplay between right vmPFC lesion size, personal relationship with God, and sense of control using mediation analyses. We tested two potential mechanisms: 1) right vmPFC damage increased sense of control by increasing personal relationship with God; 2) right vmPFC damage increased personal relationship with God by increasing sense of control.

First, we investigated the relationship between lesion size in the right vmPFC group and sense of control with personal relationship with God as the mediator. In a simple mediation analysis with right vmPFC damage entered as the independent variable, personal relationship with God entered as the mediator, and sense of control entered as the dependent variable, we found a significant indirect effect (ab = 0.006, SE = 0.0035, 95% CI = [0.00001, 0.0135]; Fig. 4A). Namely, larger right vmPFC lesion size was associated with a stronger personal relationship with God, which in turn led to stronger sense of control.

Next, we tested the alternative mechanism by reversing the mediator and dependent variable, using right vmPFC lesion size as the independent variable, sense of control as the mediator, and personal relationship with God as the dependent variable. In contrast, there was no significant mediation effect of sense of control on the relationship between right vmPFC lesion and personal relationship with God (indirect effect ab = −0.058, SE = 0.0365, 95% CI = [−0.1399, 0.0034]; Fig. 4B). This pattern of results supports a model of right vmPFC damage enhancing participants' sense of control through enhancing their personal relationship with God.

A note about cognitive flexibility and open personality as potential mediators

A previous study by our group (Zhong et al., 2017) found that cognitive flexibility and open personality mediated the association between brain damage (in the dorsolateral PFC) and religious fundamentalism, suggesting that these factors are essential components in religious beliefs. Given that in the current analysis we similarly found that a personal relationship with God was correlated with less cognitive flexibility and less open personality (see Section 3.2), we decided to test the potential role of these factors as mediators between right vmPFC damage and personal relationship with God.

We first investigated the relationship between lesion size in the right vmPFC and personal relationship with God with cognitive flexibility as the mediator. A simple mediation analysis revealed no mediation effect (ab = 0.069, SE = 0.049, 95% CI = [−0.002, 0.189]; Supplementary Figure 1A). Next, we investigated the relationship between lesion size in the right vmPFC and personal relationship with God with openness as the mediator. Once again, we found no mediation effect (ab = 0.008, SE = 0.0379, 95% CI = [−0.059, 0.097]; Supplementary Figure 1B).

Table 2 Demographics and neuropsychological measures (mean (SD)) for veterans with no head injury (Healthy control, HC group), veterans with posterior cortex damage (brain damage control, PC group) and veterans with right vmPFC damage (R vmPFC group)

Variables\group	HC	PC	R vmPFC	Statistics
Demographics:				
Age (years)	63.77 (3.84)	63.38(2.33)	62.62(2.40)	F(2,58)=.618, *p*=.543
Education (years)	15.50 (2.02)	15.23 (2.34)	13.46(2.47)	F(2,58)= 3.68, *p*=.031
Handedness (L:R:A)[1]	4:16:2	4:21:1	0:13:0	X^2 (4)=4.466, *p*=.347
Experimental measures:				
Personal Relationship with God	41.31 (18.51)	43.92(19.44)	59.76(14.92)	F(2,58)=4.57, *p*=.01
n	22	26	13	
Sense of control	3.64 (1.25)	3.27 (0.87)	2.46(1.26)	X^2 = 6.39, *p*= .04
n	22	26	13	
Control measures:				
Pre-injury IQ[2]	68.77 (19.82)	69.64 (24.52)	58.08(22.71)	F(2,48)=1.171, *p*=.319
n	13	25	13	
Post-injury IQ[2]	70.33 (21.78)	63.69 (27.11)	45.50(23.51)	F(2,54)=3.458, *p*=.039
n	21	26	10	
Empathy[4]	19.33 (29.21)	27.27 (27.78)	34.38 (25.60)	F(2,57)=1.218, *p*= .304
n	21	26	13	
Affective ToM [4]	79.17 (16.01)	77.04 (14.23)	76.73 (12.47)	F(2,54)=.156, *p*= .856
Affective ToM-Control [5]	97.14(3.38)	96.00(4.78)	95.27(4.67)	F(2,54)=.539, *p*= .586
n	21	25	11	
Depression[6]	8.05 (8.47)	6.73 (5.47)	6.54 (7.50)	F(2,58)=.268, *p*=.766
n	22	26	13	
PTSD[7]	80.24 (23.58)	77.88 (24.19)	74.15 (21.54)	F(2,57)=.270, *p*=.764
n	21	26	13	
Total Brain Volume Loss	n/a	18.62(20.13)	54.23(37.67)	t(37)=3.87, *p*=.000
n		26	13	
Religious Person? (Y:N)[8]	13:9	16:10	16:10	X^2 (2)=2.685, *p*= .261
n	22	26	13	
Religion Raised?(P:RC:N:O)[9]	9:8:2:2	18:3:2:2	7:4:1:0	X^2 (10)=8.640, *p*= .567
n	21	25	12	

[1] Handedness (L:R:A): left, right, 1 and ambiguous

[2] Percentile score of Armed Forces Qualification Test (AFQT)

[3] Balanced Emotional Empathy Scale (BEES) Total empathy raw score

[4] Faux Pas story/Faux Pas questions score

[5] Faux Pas story/Control questions score

[6] Beck Depression Inventory-II (BDI-II) total score

[7] Mississippi Post Traumatic Stress Disorder scale

[8] "Do you consider yourself to be a religious person?" (Y:N), yes and no

[9] "What religion were you raised in?" (P, RC, N, O: Protestant, Roman Catholic, None, and Other)

Discussion

This study is the first to provide causal evidence for the neural basis of a personal relationship with God and its link to one's sense of control. First, our masked VLSM analysis provides evidence that the right vmPFC is causally involved in modulating a personal relationship with God. This finding is in accordance with previous studies associating other aspects of religiosity with the vmPFC (Asp et al., 2012; Ferguson et al., 2018; Zhong et al., 2017). Second, we found that right vmPFC damage was associated with elevated levels of sense of control, as was self-reported by participants. Finally, our mediation analysis indicated that

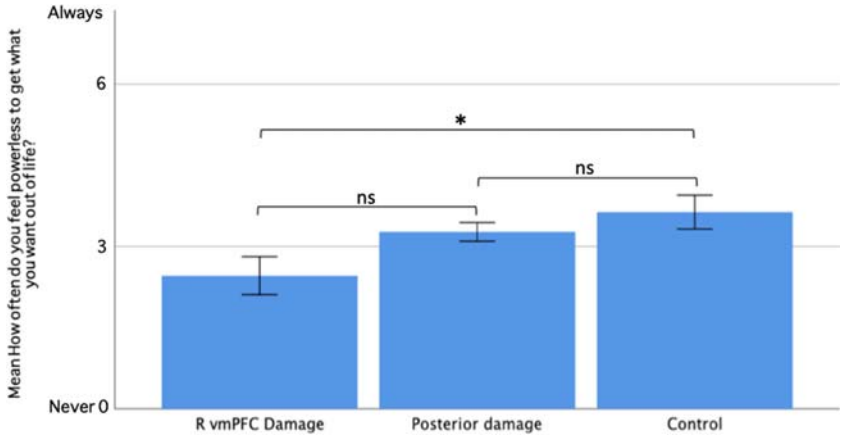

Fig. 3 Group difrences on sense of control measure. Individuals with right vmPFC damage (n = 13) reported feeling less powerless (higher sense of control) compared with healthy controls (n = 22, $p = 0.021$) but were not different from individuals with posterior damage (n = 26, $p = 0.15$). There was no difference between the posterior damage and healthy control groups ($p = 0.61$). Error bars stand for one standard error. *$p < 0.05$; ns: $p > 0.05$

right vmPFC damage increases a sense of control via the heightening of a patients' personal relationship with God.

Our findings indicate the importance of the close link between belief in God and a sense of control, and strengthen theories claiming that religion originated, at least in part, from the desire to avoid the threatening experience of perceiving the world as random and chaotic. According to this framework, having a personal relationship with God can restore a sense of control when it has been lost (Kay et al., 2008; Laurin et al., 2008). Furthermore, our results establish a crucial role for the right vmPFC in relation to both concepts. We will next discuss specific aspects of the reported findings separately.

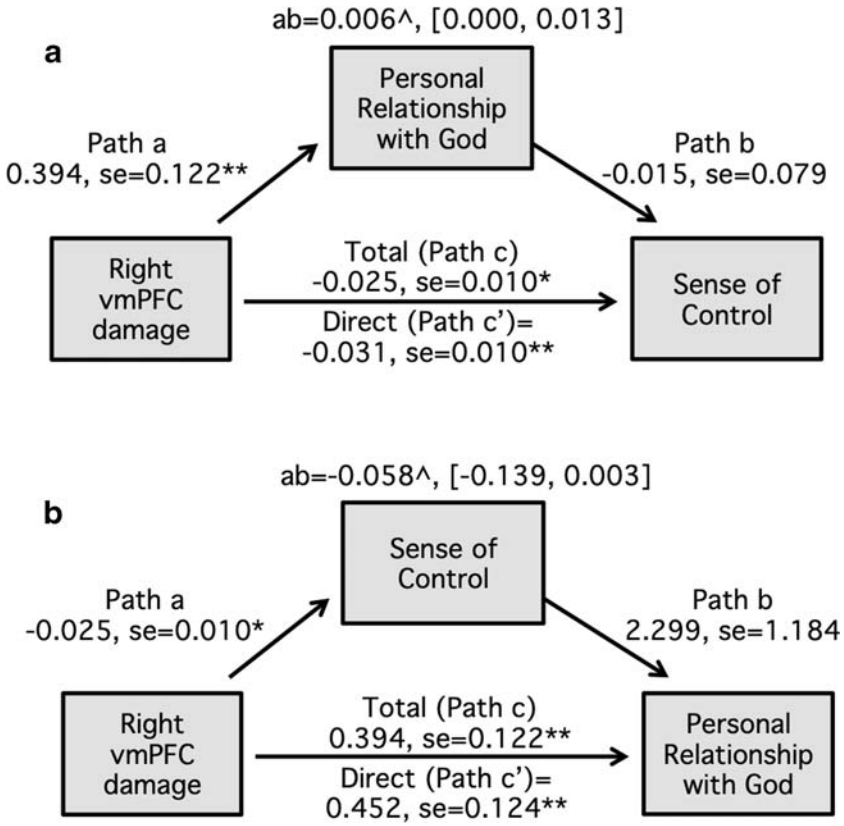

Fig. 4 Results of the mediation analysis testing the relationship between vmPFC lesion, personal relationship with god and sense of control. The diagrams show the coefficients and SE of the path model significant at *$p < 0.05$ and **$p < 0.01$. ^Indirect path coefficient (lower and upper limit of the confidence interval)

vmPFC and personal relationship with God

While our findings suggest that there is a causal relationship between vmPFC and a relationship with God, it is possible that this association is mediated by other variables. In our study, we ruled out cognitive flexibility and open personality as potential mediators; however, other cognitive abilities or personality traits associated with vmPFC (e.g., empathy, trust, or confidence) should be examined as potential mediators in future studies.

Interestingly, while this and other lesion studies show that *damage* to the vmPFC results in increased religious experience (Asp et al., 2012; Zhong et al., 2017), functional imaging studies are linking *activation* in this region to increased religious experience (Ferguson et al., 2018). While this may seem as a discrepancy at first, we suggest that this is not the case. In our view, the vmPFC does not directly enhance one's personal relationship with God. In contrast, given that patients with lesions in this area reported a *stronger* personal relationship with God, we infer that it is likely that other, intact brain areas, enabled the strong personal relationship with God observed in these patients, and that the vmPFC normally plays an *inhibitory* role in modulating this effect. This is consistent with previous claims for an inhibitory role of the vmPFC on limbic structures (Dillon & Pizzagalli, 2007) and in relation to controlling emotions (Moretti, Dragone, & di Pellegrino, 2009). We argue that this inhibitory role is reflected by stronger activation in the vmPFC observed in imaging studies.

Personal relationship with God and sense of control

While in this study we found an association between a stronger personal relationship with God and higher sense of control, several previous studies examined this association from a different angle, linking a *loss* of sense of control and a *stronger* belief in God (Kay et al., 2008, 2010). Moreover, a recent field study found that experiencing war—an experience that often is chaotic and can lead to feelings of powerlessness—*increases* people's religiosity (Henrich, Bauer, Cassar, Chytilová, & Purzycki, 2019). Based on these findings, we might have predicted a link between a diminished sense of control (often reported shortly after TBI) and stronger personal relationship with God. However, it is important to note that our findings do not reflect the potential loss of control that might be experienced *immediately* following a TBI. The data analyzed here were collected 30-45 years post-injury and reflect the link between damage to a key brain region modulating the cognitive and emotional aspects of a personal relationship with God and the sense of control—independent of a current crisis. It is possible that shortly after their brain injury, our participants first experienced a loss of control, which was followed by a stronger personal relationship with God, which led to a stronger sense of control (at least in the vmPFC patients); however, we could not directly test this hypothesis in the current study.

Overall, the findings from this study support theories claiming that a personal relationship with God allows one to perceive oneself as having control over their lives (Kay et al., 2008; Landau, Kay, & Whitson, 2015; Norenzayan et al., 2016). However, it is important to note that a personal relationship with an unpredictable, interventionist God may actually decrease a sense of control (Kay, Laurin, Fitzsimons, & Landau, 2014; Khenfer, Laurin, Tafani, Roux, & Kay, 2017). Future studies that identify the type of God people are reporting a relationship with will provide a more nuanced understanding of whether and how the type of God mediates the association between a personal relationship with God and sense of control.

Brain damage and sense of control

Our results demonstrate an association between brain damage and stronger sense of control. This finding is counterintuitive, and one may argue that right vmPFC lesions do not improve control over one's life, but rather distorts the perception of control, which can result in patients reporting having more control when it is not the case. While in this study we could find no evidence that right vmPFC lesion distorts the ability to accurately reflect upon one's life, future research is needed to compare self-report regarding sense of control to objective measures in patients with TBI to shed light on this issue.

Laterality effect

Our results propose that the right vmPFC plays a more central role than the left vmPFC in regards to modulating a personal relationship with God and sense of control. This finding in an all-male sample, such as ours, supports previous claims that argued that in male samples *the right* vmPFC is specifically linked to deficits in emotional processing and decision-making (Tranel et al., 2005).

Final notes

While the vmPFC plays an important role in shaping a personal relationship with God, it is clearly not the only brain region related to religious belief. For example, healthy volunteers in a functional neuroimaging study (Kapogiannis et al., 2009) activated an extended network of structures within and beyond the PFC when endorsing statements about God's perceived level of involvement in their lives, including the dorsomedial prefrontal cortex, the ventrolateral prefrontal cortex, and the inferior parietal lobule (for a recent review of the neural basis of religious cognition see Grafman et al., 2020).

The notion that vmPFC damage leads to a stronger personal relationship with God does *not* imply that individuals who have a strong relationship with God have any kind of brain malfunction. This study was designed to infer the role of different brain regions in modulating religious belief at the group level. A wide diversity of normal experiences and brain regions act simultaneously to guide each individual to a particular relationship with God.

Limitations

Our study has a number of limitations. First, a personal relationship with God was measured several years after data regarding sense of control was collected. While this is not ideal, previous findings suggest that measures of religiosity are relatively stable throughout mid-life (Hayward & Krause, 2013), and therefore we argue that these measures are valid to use together. More importantly, our main hypothesis does not focus on the absolute ratings but on the *difference* between certain groups, and there is no reason to assume that the time gaps will impact the groups differently.

Second, sense of control in this study was assessed based on responses to a single item and not based on a full scale. Given that theories in clinical and social psychology define control using different—yet overlapping—constructs, such as self-efficacy, mastery orientation, and goal achievement (Landau et al., 2015), it may not be entirely clear which aspect of control was measured in this study. Therefore, it is recommended that future studies use a comprehensive questionnaire rather than a single question to improve the theoretical and psychometric validity of sense of control.

Third, it is worth noting that the effect for a personal relationship with God as a mediating factor between right vmPFC lesion and greater sense of control was small. Therefore, we assume that there are probably other factors that might mediate this association.

Finally, the sample in our study only included older male participants. Older adults report religion to be more integral to their lives than do younger adults (Pew Research Center, 2018), and a previous study (Jackson & Bergeman, 2011) found that perceived control is a stronger mediator of the relationship between religiosity and life satisfaction for older compared with younger adults. Thus, the results might not be generalizable to younger or female samples. Although our study leaves some questions unresolved, it nevertheless offers novel data to support the theory that experiences of a personal God enhance the subjective sense of control.

Conclusions

Our findings demonstrate that a strong personal relationship with God can serve an important psychological function by affecting sense of control, and this aspect of belief is enhanced following damage to the human right ventromedial prefrontal cortex. We speculate that it may be useful for patients with brain damage and their significant others to consider drawing on their faith traditions to help improve their sense of personal control post-injury and thereby improve their outcome (Puchalski & Romer, 2000), particularly following right vmPFC damage.

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Compliance with ethical standards

Conflict of interest The authors have no conflict of interest to declare.

Open practices statement The data that support the findings of this study are available from the corresponding author upon reasonable request. This study was not preregistered.

Appendix

Personal Relationship with God Scale

- God does not notice me.*
- God lifts me up.
- I am never really sure that God is really listening to me.*
- God doesn't feel very personal to me.*
- I can talk to God on an intimate basis.
- I get no feeling of closeness to God, even in prayer.*
- I feel that God knows me by name.
- God never reached out to me.*
- I feel warm inside when I pray.
- God does not answer when I call.*
- Prayer is very meaningful to me.
- I prefer to face my problems without prayer.*
- God tells me what he wants from me.
- I do not think about God very often.*
- In my religious experience, I felt that God or a higher power communicated with me.
- I find a precise meaning was communicated to me through my religious experience.
- My religious experience filled me with strong emotion.

*Reverse Items

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