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Modelling terror management theory: computer simulations of the impact of mortality salience on religiosity

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ABSTRACT

This article outlines the development – and reports on the experimental findings – of two computational models designed to simulate the dynamic systems and behavioural patterns identified and clarified by research on terror management theory. The causal architectures of these models are informed by empirical research on the effects of mortality salience on "religiosity" (and vice versa). They are also informed by research on the way in which perception of personal and environmental hazards activate evolved cognitive and coalitional precautionary systems that can intensify anxiety-alleviating behaviours such as imaginative engagement with supernatural agents postulated within a religious coalition. The capacity of the models to produce emergent patterns and behaviours that are similar to the results of other empirical studies supports the plausibility of their causal architectures. After tracing some of the literature that supports the causal dynamics of our models, we present the two models, describe the experiments, and report the results. We conclude by discussing the importance of the findings, the limitations of the models, and directions for future research.

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Introduction

As the editors of this special issue point out in their foreword, empirical research on the relationship between terror management theory (TMT) and religion in recent decades has provided significant support for the hypothesis that supernatural ideas and religion can serve as a particularly powerful way to mitigate the awareness of death (Arrowood, Vail, Jong, & Hood, in press). The other articles in this issue offer new insights into the way in which mortality salience impacts – and is impacted by – a variety of religious beliefs, attitudes and behaviours, thereby providing additional evidence for the value of TMT in the scientific study of religion.

This article contributes to the burgeoning literature in this interdisciplinary field by reporting on the first attempt to develop computational architectures that simulate some of the most relevant factors shaping the reciprocal interaction between religiosity and mortality salience. Scholars in the biological and social sciences are increasingly taking advantage of techniques in modelling and simulation (M&S), which are said to form a "third pillar" of science, alongside theory and experimentation (Yilmaz, 2015), and a "fourth paradigm" of science, building on empirical, theoretical,

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and computational methodologies (Hey, Tansley, & Tolle, 2009).[1] Such approaches are also taking root in the biocultural study of religion (Bainbridge, 1995, 2006; Braxton, Upal, & Nielbo, 2012; Matthews, Edmonds, Wildman, & Nunn, 2013; McCorkle & Lane, 2012; Shults & Wildman, in press; Sørensen & Nielbo, 2013; Upal, 2005, 2015; Whitehouse, Kahn, Hochberg, & Bryson, 2012; Wildman & Sosis, 2011). We believe that this new approach can be a useful tool for testing theories against empirical data, for evaluating the assumptions of theories, for understanding the interactions between theories, and for generating new data that can themselves be the target of scientific inquiry. Our use of simulation as a tool to reconstruct and formalize some of the TMT arguments engaged by the other articles in this special issue is meant as a *methodological* complement to their primarily experimental psychological approaches.

Our contribution is also intended to be *materially* complementary by balancing the primarily intra- and inter-personal foci of the other articles with a more intense focus on the sociopolitical factors that impact the relationship between mortality salience and religion. TMT is one of the most relevant theories for understanding the social consequences and causal dynamics of human responses to acts or threats of political terror (Pyszczynski, Greenberg, & Solomon, 2003). It has also been extensively utilized in the study of religious phenomena (Halberstadt & Jong, 2014; Jong, 2014; Jong et al., in press).

While no model can incorporate all of the relevant factors within such a complex, dynamic system, the use of computer simulation can facilitate conceptual clarification and provide a new way of "experimenting" on the reciprocal relation between mortality salience and religiosity. We begin by tracing some of the theoretical and empirical literature upon which our construction of the causal architecture of terror management is grounded. Subsequently, we describe the two models we have developed, and report on our attempts to validate the results. We conclude by discussing the importance of the findings, the limitations of the models, and directions for future research.

Terror management, terrorism, and "religiosity"

Expanding on the insights of Ernest Becker in *Escape from Evil* (1985) and *The Denial of Death* (1997), TMT asserts that the human reaction to the anxiety evoked by awareness of death involves the construction and maintenance of cultural worldviews that help to bolster self-esteem, psychological equanimity, and a sense of meaning. When mortality becomes salient (e.g., when confronted by reminders of death or life-threatening hazards), implicit worldview-defending tendencies are somewhat automatically activated in order to relieve anxiety and promote survival-enhancing strategies. Natural disasters can be terrifying, evoking worldview defences that appeal to supernatural causes. For example, many religious conservatives interpreted the 2004 tsunami in southeast Asia as the judgement of God (or Allah, or the sea gods). More recently, a longitudinal study before and after the 2011 earthquake in Christchurch, New Zealand, found an increase in belief in God and religious affiliation among those most directly impacted by the event (Sibley & Bulbulia, 2012).

Of course, people can be scary too. One of the most well-documented findings in the TMT literature is that mortality salience can increase the tendency to perceive cultural and religious others as dangerous, as well as a willingness to act punitively or aggressively toward them. In fact, the impact of death awareness on attitudes and behaviours toward out-group members has been a theme that has long interested several of the leading proponents of TMT. Research over the decades has demonstrated that mortality salience increases willingness to punish moral transgressors that threaten one's worldview (Rosenblatt, Greenberg, Solomon, Pyszczynski, & Lyon, 1989) and leads to the escalation of out-group derogation and religious extremism (Greenberg et al., 1990). Several other studies have suggested that inter-group aggression and conflict can be intensified by fear of death (McGregor et al., 1998; Pyszczynski, Motyl, & Abdollahi, 2009).

After the terrorist attacks on the United States in 2001, three of the founders of TMT devoted an entire book to this theme: *In the Wake of 9/11: The Psychology of Terror* (Pyszczynski et al., 2003). Since then, a growing number of scholars have attempted to shed light on the evolutionary origins and psychological dynamics of religious terrorism, and sought to find resources for diminishing it (Juergensmeyer, Kitts, & Jerryson, 2012; Sosis, Phillips, & Alcorta, 2012). The task of tempering this evolved default is all the more difficult because of neurologically grounded *implicit* cognitive dispositions that shape the evaluation – indeed, the very perception – of other people in ways that reinforce inter-group bias (Henry, Bartholow, & Arndt, 2010). These sorts of mechanisms can exacerbate anxiety about, and activate antagonism toward, religious out-groups while operating under the radar, so to speak, of conscious reflection.

A deeper understanding of the dynamics of "religious terror" will require even more attention to the underlying causal mechanisms described above. This is why our computational architectures also incorporate insights from research on other evolved cognitive defaults such as the "hazard precaution system." The perception of (or anxiety about) threatening hazards such as natural disasters or predators can suddenly require cognitive control of normally autonomous behaviours, which swamps working memory and leads to mental and emotional stress. The hazard precaution system can help to alleviate stress by activating default behaviours such as repetitive action. Ritualized behaviours are the most obvious way in which this system is manifested in religion (Liénard & Lawson, 2008). Boyer and Liénard (2006) propose that threat detection mechanisms evolved to deal with direct threats to fitness, such as the presence of a predator or obvious contagion. These are the *proper domain* of threat detection mechanisms because the latter evolved in direct response to the presence of such stimuli. However, Boyer and Liénard further propose that the hazard precaution system broadened to respond to *potential* threats that are not necessarily observed in the environment; this is the *actual domain* of threat-detection mechanisms.

Another relevant example is the "security motivation system," which activates similar sorts of behaviours that can alleviate the stress associated with potential threats. In this case, the anxiety associated with such hazards is mitigated by promoting behaviours that strengthen a person's sense of security (Hinds et al., 2010; Woody & Szechtman, 2011). Such behaviours include the formation and protection of alliances, which play a rather obvious role within religion. It makes sense that cognitive mechanisms for detecting threats and coalitional mechanisms for protecting alliances would reinforce one another. Boyer and colleagues have argued for the role of what they call a "coalitional cognitive system," which evolved in order to "garner support from conspecifics, organize and maintain alliances, and increase an alliance's chance of success against rival coalitions" (Boyer, Firat, & Van Leeuwen, , 2015) in response to environmental threats.

These systems have been documented in non-human animals (Eilam, Izhar, & Mort, 2011), but their activation in human life is further complicated by the employment of worldviews that include references to (and ritual engagement with) culturally postulated supernatural agents. What, exactly, is the relationship between *religiosity* and the variables at work in systems such as terror management, hazard precaution, security motivation and coalition protection?

The answer to this question depends, among other things, on what we mean, exactly, by "religiosity." As Jong and colleagues have noted, one of the problems in summarizing and comparing research findings in this field is the "inconsistent operationalization of religiosity" (Jong, Halberstadt, & Bluemke, 2012). The label *religion* is (in)famously contentious and contested. In religious studies and a variety of other disciplines, the term is often used to refer to a wider set of phenomena than we focus on here. Our definitional strategy is based on our need for a concept that can be operationalized for the sake of computational modelling. Following the approach most common in the scientific study of religion, we try to avoid the quagmire of arguing about over-arching generic definitions by simply delimiting our use of key terms for the specific purposes of the project at hand: identifying a set of statistically measurable traits that consistently engender recurrent sorts of beliefs and behaviours that mutate culturally in relatively predictable ways.

Because we are interested in modelling the basic insights of TMT as they bear on the relevant religious phenomena, we use "religiosity" in this context to designate "socially shared cognitive and ritual engagement with axiologically relevant supernatural agents postulated within one's in-group." This sort of imaginative engagement, which promotes co-operation, commitment, and cohesion in the face of out-group threats and environmental challenges, is fostered by two reciprocally reinforcing evolved dispositions: the tendency to infer human-like supernatural causes and the tendency to prefer coalition-favouring moral prescriptions when confronted with ambiguous or frightening phenomena. In other words, *religiosity* involves the intensification and integration of a hyperactive propensity toward detecting gods as hidden agents and a hyperactive propensity toward protecting in-group norms. We refer to these processes as "anthropomorphic promiscuity" and "sociographic prudery," respectively.[2]

Precautionary tales: perceiving gods and practicing rituals

Why do we think this stipulated definition is helpful in this context? It captures two of the most common findings in the research on TMT and religiosity, namely that mortality salience amplifies (1) the tendency to look for (and believe in) familiar supernatural agents, and (2) the tendency to long for (and participate in) familiar religious rituals. In other words, death awareness stimulates two religiously salient default dispositions: reliance on supernatural causality (to explain confusing or threatening events) and compliance with supernatural conventions (to ease anxiety in ritually cohesive groups). In still other words, empirical experiments guided by TMT have demonstrated that when perceptions or feelings of terror are "inputs" into the dynamic system of religiosity, the most basic "outputs" are increased anthropomorphic promiscuity (acceptance of hidden human-like forces) and sociographic prudery (resistance to engaging other cultures). Furthermore, these stipulated definitions are compatible with the literature in evolutionary psychology regarding hazard precaution, security motivation, coalitional cognition, and other similar systems.

We have space here only for a brief review of some of the TMT literature that supports our proposed computational architecture for simulating the effect of mortality salience on religiosity. One sort of "output" to which the literature attests is an increased tendency to *perceive gods* (culturally postulated, counter-intuitive, intentional forces). Experimental studies have shown that the general inclination to attribute anthropomorphic qualities to nature, especially frightening natural forces such as volcanoes, is intensified by reminders of death (Norenzayan et al., 2008). Other studies have confirmed the hypothesis that mortality salience causes the amplification of belief in supernatural agents (Norenzayan & Hansen, 2006). It seems that this evolved cognitive system is calibrated to detect the gods of one's own religious coalition. For example, in one recent study in which participants were primed to think about death, Christians tended to increase their belief in the existence of God/Jesus and their denial of Allah, whereas Muslims tended to increase their belief in Allah and denial of God/Jesus (Vail, Arndt, & Abdollahi, 2012).

Another sort of "output" is an increased tendency to commit to *practising rituals* that help to establish and maintain the identity of one's in-group. Here too "hazard precaution" (and other) systems play an important role in motivating ritual behaviours (Keren, Boyer, Mort, & Eilam, 2013; Woody & Szechtman, 2011). Existential anxiety about the risk of death from uncontrollable (or unidentifiable) sources can be culturally manipulated and assuaged by religious rituals. In turn, "successful completion of the ritual performance … authenticates the belief in culturally sanctioned supernatural agents" (Norenzayan & Hansen, 2006, p. 174). This helps to explain why mortality salience can trigger human interest in participating in synchronic, emotionally arousing, causally opaque behaviours that allegedly engage the supernatural agents of one's coalition. Unfortunately, such behaviours promote not only the coalescence of religious in-groups and the associated co-operative behaviour but also anxious and aggressive attitudes toward members of out-groups (Sosis et al., 2012).

We refer to this brief narrative about these two broad types of mechanism that engender religiosity as "precautionary tales" because both anthropomorphic promiscuity and sociographic prudery seem to have evolved as ways of reacting to potential hazards. John Bowlby hypothesized the natural selection of a human "attachment behavioural system" that reinforces the tendency of infants to seek proximity to caregivers (and vice versa) when feeling anxious. The relationship between attachment style and the way in which people typically seek proximity to an imagined supernatural caregiver (e.g., God as a "safe haven") is well attested (Granqvist, Mikulincer, Gewirtz, & Shaver, 2012).

Like the tendency to scan for supernatural attachment figures, the tendency to engage in ritualized behaviour seems to be a spontaneous response to anxiety (Lang, Krátký, Shaver, Jerotijević, & Xygalatas, 2015). It makes sense that this sort of hypersensitivity to threats would have granted a survival advantage in early ancestral environments. It also makes sense that risk-aversion strategies that reinforce in-group bonding could contribute to contemporary expressions of punitive behaviour toward non-reciprocating moral transgressors (Schindler, Reinhard, & Stahlberg, 2012) and of terrorist behaviour toward religious out-groups (Lane, 2011). But are there other mechanisms for which we need to account if we are to provide an adequate model of the function of religiosity on (and within) what we will refer to as the "terror management system" (TMS)?

Mortality salience: causal and moderating factors

Anthropomorphic promiscuity and sociographic prudery may be two of the most relevant outputs of increased death awareness but there are other factors that can moderate its effect on religiosity. As Pyszczynski and colleagues pointed out over a decade ago, variables such as "high self-esteem, a liberal political orientation or salient reminder of the value of tolerance, a confident belief in symbolic immortality, and secure attachment style … serve to reduce the otherwise pernicious effects of mortality salience" (Pyszczynski et al., 2003). Our goal, however, is not to provide an exhaustive account of all possible variables within (or influences on) the TMS, but to abstract some of the most religiously salient causal mechanisms studied in the literature in order to model them within computer simulations and provide another way of validating them experimentally.

Religiosity may help many people deal with their anxiety about death, but it does not help everyone in the same way or to the same extent. Much of the recent literature on TMT and religion has drawn attention to the role of *prior religiosity* in moderating the effects of mortality salience. The research by Lifsin et al. (Lifshin, Greenberg, Soenke, Darrell & Pyszczynski, in press) in this volume, for example, demonstrates the impact of low religiosity on belief in the afterlife and support for indefinite life-extension technologies. Earlier studies have shown that people who are highly religious, or report a strong sense of religious identity, are far more likely to detect (their own, as well as other) supernatural agents when primed to think about death (Jong, 2014; Jong, Bluemke, & Halberstadt, 2013). Both believers and non-believers may experience an *implicit* activation of religiosity when confronted with thoughts of death, but believers manifest an increase in *explicit* religiosity (Jong, 2014). The effect seems to hold cross-culturally. For example, a recent Chinese study found a significant difference in the way Christians and unbelievers relate to material goals (and "other-worldliness") after experiencing a life event carrying an existential threat (Hui, Chan, Lau, Cheung, & Mok, 2012).

The moderating effect of prior religiosity is itself influenced by the extent to which that religiosity can be characterized as *fundamentalist* and the extent to which it is shaped by an *intrinsic* orientation. As Routledge et al. point out in this issue, "fundamentalists are motivated to perceive destructive events in the world as consistent with a prophesized apocalypse" (Routledge, Greenberg, Soenke, & Pyszczynski, in press, p. 14). Earlier studies have suggested that religious beliefs are particularly well suited to mitigate death anxiety because they rely on concepts that are not easily disconfirmed, and promise literal (not merely symbolic) immortality. Fundamentalists in particular are more likely to take religious beliefs literally and to resist their disconfirmation (Rothschild, Abdollahi, & Pyszczynski, 2009; Vail et al., 2010). Religious people who are more uncertainty averse will tend to react with intensified zeal when threatened (Mcgregor, Nash, & Prentice, 2010), and utilize compensatory control strategies leading them to have "unrealistic convictions about their idiosyncratic opinions and values and the objectivity and social consensus for those opinions and values" (Kay, Gaucher, Mcgregor, & Nash, 2010). Other similar studies provide cross-cultural confirmation of these sorts of dynamics (Yen & Lin, 2012).

Other factors that have been demonstrated to have a moderating effect on people's reactions to mortality salience include *attachment style* (Mcgregor, Prentice, & Nash, 2012; Taubman-ben-ari, Findler, & Mikulincer, 2002) and *self-esteem* (Du et al., 2013; Schmeichel et al., 2009). It may seem odd, therefore, that the causal architectures of our models do not include these and other variables. One reason for this decision is pragmatic: because we want our system-dynamics model and our agent-based model to be as similar as possible, we have left out the sort of personality factors that would only be relevant for the latter. Another reason is more material: factors such as the level of intrinsic orientation and the extent to which religiosity is implicitly activated are not directly relevant for our current purposes because we are interested in the *explicit* religiosity "outputs" identified above, which empirical research suggests are primarily connected to prior religiosity (and fundamentalism).

TMT scholars are often interested in the *causal* relationship between religiosity and death anxiety (Jackson et al., in press) as well as correlational analyses (Jong et al., in press). They also tend to be methodological pluralists. For example, the authors of a recent analysis of the motivation for aggressive religious radicalization encouraged testing hypotheses in a variety of ways: in the laboratory, through interview studies, and in real-world interventions (Mcgregor, Hayes, & Prentice, 2015). We believe that M&S methodologies have a unique role to play in this ongoing research, not least because of the way in which they enable analysis of (and even experimentation with) the *causal* dynamics of complex systems. M&S techniques allow us to move beyond questions about correlations and engage in what Epstein (2013) has called "generative" social science: explaining the generative causes that alter a dynamic system or the behaviours of agents in coalitions. The models we propose here provide a significant contribution to the literature because they incorporate multiple theories in the threat detection literature, and integrate many aspects of the terror management, hazard precaution, and security motivation systems. By addressing both the actual and proper domains of these cognitive mechanisms, we can provide a general cognitive architecture for understanding how human beings navigate many types of threats within an evolutionary framework.

Our goal in what follows is to model the effect of mortality salience on religiosity (as defined above) and vice versa. Each of our simulations is focused on the relevant inputs and outputs that shape the ways in which (more or less religious) agents adapt to waves of threatening, anxiety-producing events, and so we call them "natural adaptation to hazard undulation models" (NAHUM).[3] In order to test the theoretical claims outlined above, we constructed our models using the Any Logic software, version 7.2 (The AnyLogic Company, 2015). The first model is a system-dynamics model (SDM). SDMs attempt to formalize the causal architecture of a complex non-linear system using stocks (storage of some units in the model), flows (movement of units between stocks), time delays, and the interactions of variables that may form positive or negative feedback loops. The second model is an agent-based model (ABM). ABMs implement rules of behaviour for individual agents who interact within a simulated environment. Agents can interact with one another and with the environmental variables in the simulation. For detailed descriptions and source code for all models discussed in this paper, see the Supplementary Materials (https://github.com/SimRel/20160417_NAHUM).

System-dynamics model

The architecture of our SDM attempts to incorporate only those relationships that are necessary to produce the outputs discovered by TMT research. A visual depiction of the relationships can be seen in Figure 1. The square boxes are stocks, which indicate levels of religiosity (as defined above). The thick arrows between stocks represent flows of religiosity. The circles represent variables that have an effect on either stocks or flows; circles with wedges are parameters for the simulation and are fixed at the start of each simulation run, while the circles without wedges are dynamic and change during the course of a run.

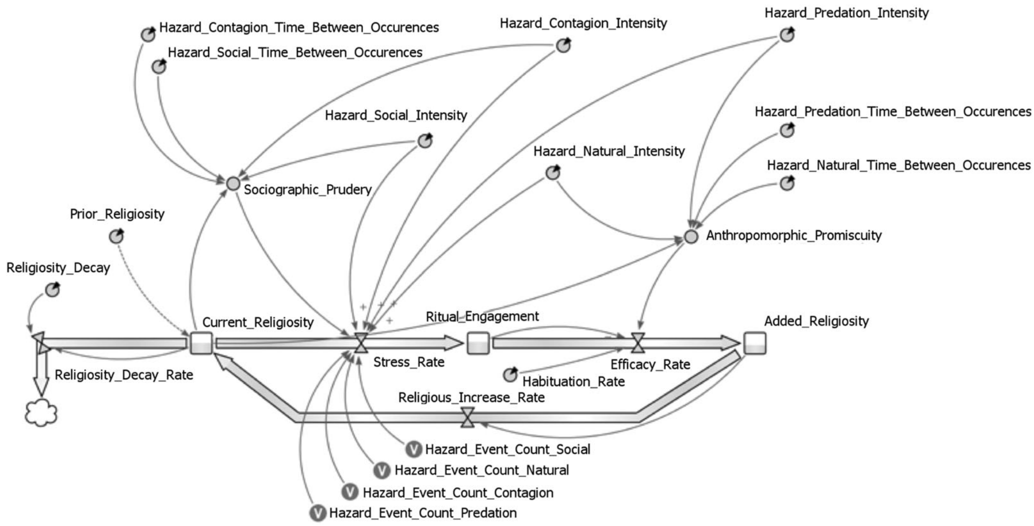

Figure 1. Depiction of NAHUM-SDM variables and their interactions (for details and source code, see Supplementary Materials).

Variables in the SDM

The NAHUM-SDM variables are of two types. First, there are the "personal" variables related to the simulated individual. Second, there are "environmental" variables related to four types of hazard (social, contagion, natural, and predation). All of these variables – and the postulated relationships among them – are drawn from the literature outlined above. Each of the environmental hazard variables has two aspects (an occurrence rate and an intensity) that increase religiosity outputs, which in turn decay over time at a particular rate (*Religiosity_Decay_Rate*) as determined by a model parameter (*Religiosity_Decay*). Encounters with social and contagion hazards increase sociographic prudery (SP), while natural and predation hazards increase anthropomorphic promiscuity (AP).

The two decay rates in the model, *Religiosity_Decay* and *Habituation_Rate*, require some explanation. *Religiosity_Decay* represents the rate at which an individual's heightened levels of AP and SP (i.e., religiosity) decay over time. This is related to what Whitehouse has called the "tedium effect" (Whitehouse, 2004). The lower the value of the *Religiosity_Decay* variable, the more slowly religiosity decays after a threat. *Habituation_Rate* is a measure of the rate at which an individual's reliance on religious ritual to mitigate threat-induced stress declines. This is related to what is sometimes called "yedasentience" in the security motivation system literature (Hinds et al., 2010; Woody & Szechtman, 2011). The lower the value for the *Habituation_Rate* variable, the more slowly belief in the efficacy of ritual interventions to manage terror declines (i.e., the longer it takes to become habituated to the threatening event).

The arrows in Figure 1 depict the interaction of the variables. Note that each of the thicker arrows also include a flow-rate adjustment, which affects the flow of religiosity from one stock to another. The static variables (circles with wedges) affect these flow rates as well as the dynamic variables in the model.

During the testing process we noticed that the simulation was replicating general habituation curves (see Figure 2). That is to say, in the presence of a new stimulus (a hazard), there was a positive increase in the model's output (the simulated individual's religiosity), but then habituation set in and the output began to drop. This habituation–reaction curve has been discussed at length in the psychological literature (e.g., Rescorla & Wagner, 1972) and in the computer modelling literature (e.g., Epstein, 2013).

The microperturbations depicted in Figure 2 provide some initial warrant for the plausibility of the causal architecture employed in the model, but they are not a particularly important result of the

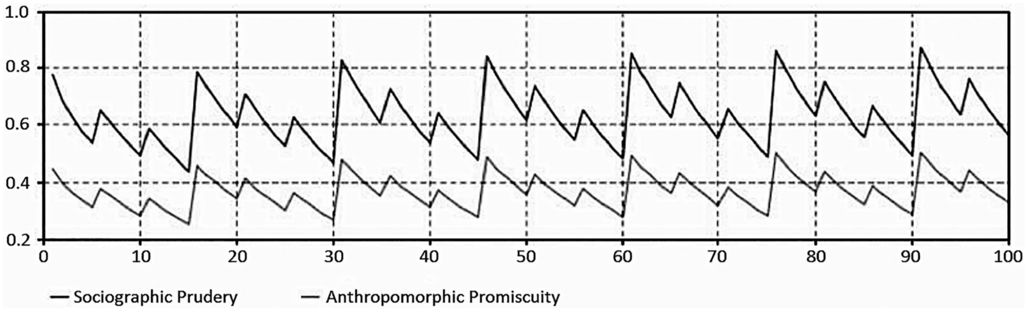

Figure 2. Rescorla–Wagner diagram for NAHUM-SDM, showing religiosity changes over time (using simplified model parameters to clarify the diagram). Output is scaled so that SP and AP run between 0 and 1. SP tends to be higher in this time history, but it is the relative change in each variable that matters in this diagram.

experimental design. After all, such behaviours can be mathematically calculated without the need for computer simulations. Because the goal of our experiments was to contribute to a broader understanding of the cognitive and coalitional dynamics at work in the TMS, our primary focus was on the complex, non-linear dynamic interactions of the system as it runs over time in different simulated environments. The top (darker) line of Figure 2 represents the value of SP and the bottom (lighter) line represents AP.

Design of experiment

To test the ability of the SDM to produce outcomes that replicate findings in the ethnographic record and from psychological experimentation, we set up experiments that explored the conditions under which one can detect the emergence of four trends over time: (1) the maintenance of AP and SP, (2) a steady increase of AP and SP, (3) a steady decrease of AP and SP, and (4) a cycling between low and high levels of AP and SP. This sort of experimentation is not primarily focused on the correlation between variables ("how is x statistically related to y"?) but with grounding or causal relationships ("under what conditions does the system exhibit behaviour z?"). In an attempt to answer this latter kind of question, we ran optimization experiments that specified the four trends (above) as targeted output conditions. We then analysed the simulated data by searching the possibility space of the model under different parameter combinations in order to find the combinations that best approximated each of the four target conditions.

Results

It turns out that NAHUM-SDM can produce all four targeted behavioural trends quite well. In fact, we found an optimal solution for each of the output states. As is often the case, there is a region in the parameter space around each optimal solution within which each type of output is typical and widespread. These are "equilibrium regimes" of behaviour within the model.

The results of the experiment are depicted in Table 1. Since we stipulatively defined "religiosity" as the combination of AP and SP, we decomposed that variable into these two components. The first four numerical columns depict the values of the parameter settings that produce the regimes of behaviour of the four targeted output conditions (maintain, increase, decrease, cyclical). Note that it is the relative, not the absolute, size of these numbers that matters. The last three columns express this relationship by recording the ratios of parameter values, which gives us a sense of the parameter changes that are necessary to shift the behavioural regime of the system from maintain to increase (I/M), from maintain to decrease (D/M), and from maintain to cyclical (C/M). We focus on these

Table 1. Results of the NAHUM-SDM experiment.

Parameters	Maintain	Increase	Decrease	Cyclical	I/M	D/M	C/M
Sociographic Prudery (SP)							
Hazard_Social_Intensity	0.00028	0.012	0.021	0.34	42.67	74.68	1223.33
Hazard_Social_Time_Between_Occurrences	36.50	8.14	50.00	11.36	0.22	1.37	0.31
Hazard_Contagion_Intensity	0.00022	0.010	0.021	12.00	45.07	94.64	54078.41
Hazard_Contagion_Time_Between _Occurrences	47.48	21.33	48.98	11.79	0.45	1.03	0.25
Anthropomorphic Promiscuity (AP)							
Hazard_Predation_Intensity	0.00028	0.025	0.036	0.268	88.06	126.81	943.99
Hazard_Predation_Time_Between_Occurrences	28.65	1.96	2.76	2.80	0.07	0.10	0.10
Hazard_Natural_Intensity	0.01	0.012	0.039	0.27	1.20	3.90	27.00
Hazard_Natural_Time_Between _Occurrences	1.00	35.00	3.65	12.50	35.00	3.65	12.50
Personal Traits							
Habituation_Rate	0.97	0.058	0.020	0.28	0.060	0.020	0.29
Religiosity_Decay	0.01	0.01	0.049	0.15	1.00	4.90	15.20

Notes: In the first four numerical columns lower numbers should be interpreted as follows: for hazard intensity, lower intensity; for hazard time between occurrences, higher frequency of threats; for habituation rate, slower to get accustomed to threats; for religiosity decay, slower decline of religiosity after a hazard event. The numbers in the last three columns are simply ratios (e.g., I/M is the ratio of Increase to Maintain).

three ratios because we regard the "maintain" output as a baseline, relative to which increase, decrease, and cyclical outputs can be compared.

The results of this experiment reveal that the model behaviour is driven by a mixture of individual-level traits (*Habituation_Rate* and *Religiosity_Decay*) and environmental stimuli (the occurrence rates and intensities for social, contagion, predation, and natural hazards). In fact, the parameters from Table 1 are also the most significant drivers of model behaviour, as changing their values leads to variations in increasing, decreasing, maintaining, or cyclical behaviours for religiosity. It is important to remember that the identification of a behavioural regime containing the optimal solution for each type of condition does not rule out the existence of other (possibly unconnected) regimes that illustrate similar (but less optimal) outcomes under other conditions. Moreover, the experimental design cannot provide a 100% guarantee that the behavioural regime containing the targeted solution is the largest or even the most important regime within the parameter space. Claims based on this experiment must therefore be framed with appropriate caution.

Understanding the output against real-world observations

In what follows, we briefly describe the conditions under which, according to the simulation experiments, the target trends are most likely to be observed. Keep in mind that NAHUM-SDM depicts an "average" person's response pattern to terrifying events. Because the focus here is on the individual, the only way to generalize to populations would be to assume that all people are like the simulated average person. As we will see below, the ABM provides a better way of exploring the *social* aspects of the TMS.

Maintain

The optimization experiment suggests that high habituation rate and low religiosity decay are key conditions for an individual's *maintenance* of a specified level of religiosity. In other words, religiosity is more easily maintained for individuals who get accustomed to dealing with threats relatively quickly, but whose religiosity is slow to decline after spiking in the wake of a threat. People's religiosity can be maintained over time when their terror-inducing stress is relieved through ritual engagement, but only if they are able to avoid the "tedium effect" (Whitehouse, 2002, 2004) and to continue believing that in-group rituals are working (i.e., efficaciously engaging the relevant supernatural agent). When it comes to environmental conditions, the experiment suggests that people who live in contexts where threats have very low intensity and moderately low frequency are more likely to maintain their level of religiosity. In fact, threats have to be lower in intensity in the "maintain" condition than any of the other three.

Increase

One of the conditions for a steady *increase* in religiosity over time is that an individual has a relatively low habituation rate, i.e., grows accustomed to hazard threats far less quickly (relative to the maintain behavioural regime). The optimal outcome for the "increase regime" occurs when individuals have a low religiosity decay rate, with their religiosity declining more slowly than in the decrease or cyclical conditions (but at the same speed as in the maintain condition). Increase in religiosity over time also occurs when threats are moderate-to-high in frequency, and of moderate intensity (but greater than in the maintain condition). Moderately frequent, moderately severe threats ratchet up stress and drive threat-induced religiosity higher over time in the presence of low habituation rate and low religiosity decay. Environmental conditions with frequent and rather intense threats to mortality, navigated by individuals who get used to threats slowly and do not lose their religiosity quickly, are most likely to produce the "increase regime".

Decrease

Experiments on the SDM indicate that very low habituation rates and relatively high religiosity decay are conditions for a steady *decrease* in religiosity over time. This target outcome tended to occur in environments with moderate-intensity hazards. However, the way in which AP and SP are affected in this behavioural regime depends on the rate at which these threats are encountered. In the optimal outcome of the decrease trend, SP decreases significantly in environments with low-frequency social and contagion hazards, while AP decreases in environments having moderately high-frequency predation and natural hazards.

Cyclical

When the personal variables are set at a relatively high habituation rate (but not as high as that needed to maintain religiosity) and a religiosity decay rate much higher than any other of the three ideal solutions in the experiment, simulated individuals tended to *cycle* between low and high levels of religiosity. Interestingly, the optimal cyclical condition arises when people encounter highly salient threats with moderately high frequency in the environment. This replicates the most common findings in the TMT literature. People are typically habituated in such a way that their religiosity is preserved at a base level. However, their level of religiosity increases in the presence of threats. They then alleviate the stress evoked by those threats by intensifying their scanning for supernatural agents and participation in the rituals of their religious coalitions, which drives their religiosity back down close to the original base level.

The relationship between AP, SP, and religiosity change in NAHUM-SDM

In order to further validate the causal architecture of the model, we also explored combinatorial patterns of AP and SP to discover how their relationship affected changes in overall religiosity. Our goal was to lend more plausibility to our claims about the mechanisms whereby AP and SP are converted into altered religiosity in a way that adequately captures the empirical results in the TMT literature.

Our exploration swept the parameter space by running the simulation more than 15,000 times with different combinations of input parameters. At the conclusion of each simulation run, we recorded the individual's AP, SP, and overall change in religiosity. Together these values form a single point in Figure 3. Plotting these points together provides insight into what combinations of AP and SP cause minor, moderate, and extreme changes in religiosity (understood as the sum of AP and SP).

The x-axis of Figure 3 reflects the range of values for AP recorded in our simulation runs. Similarly, the y-axis of Figure 3 reflects the range of values for SP. Both axes run from −40 to 50. By looking at the x- and y-values of any point on the graphic, one can see the AP and SP recorded at the beginning of a simulation run. Note that it is the relative, not the absolute, size of these values that matters. Larger values indicate higher levels of AP and SP, while smaller values indicate lower levels.

Figure 3 shows six facets, composed by two rows and three columns. The top row represents those cases in which religiosity increased from the initial level at the beginning of a simulation run to the final level measured at the conclusion of that run. The bottom row represents those cases in which religiosity decreased as the simulation ran from beginning to end. The left column shows cases in which there were minor changes in religiosity (<5), the middle column cases in which there were moderate changes (5–50) and the right column cases in which there were extreme changes (>50). Each facet presents simulation runs in which a specific type of increase or decrease in religiosity occurred and indicates the AP and SP values that produced the change. For example, the top right facet shows the AP and SP values that cause an extreme increase in religiosity level, while the bottom left facet shows the AP and SP values that result in a minor decrease in religiosity.

Finally, each point in Figure 3 is shaded according to the *distance* between the AP and SP values recorded in a given simulation run. Darker values represent smaller distances (0–8), grey values represent moderate distances (8–12), and lighter values represent large differences (12+).

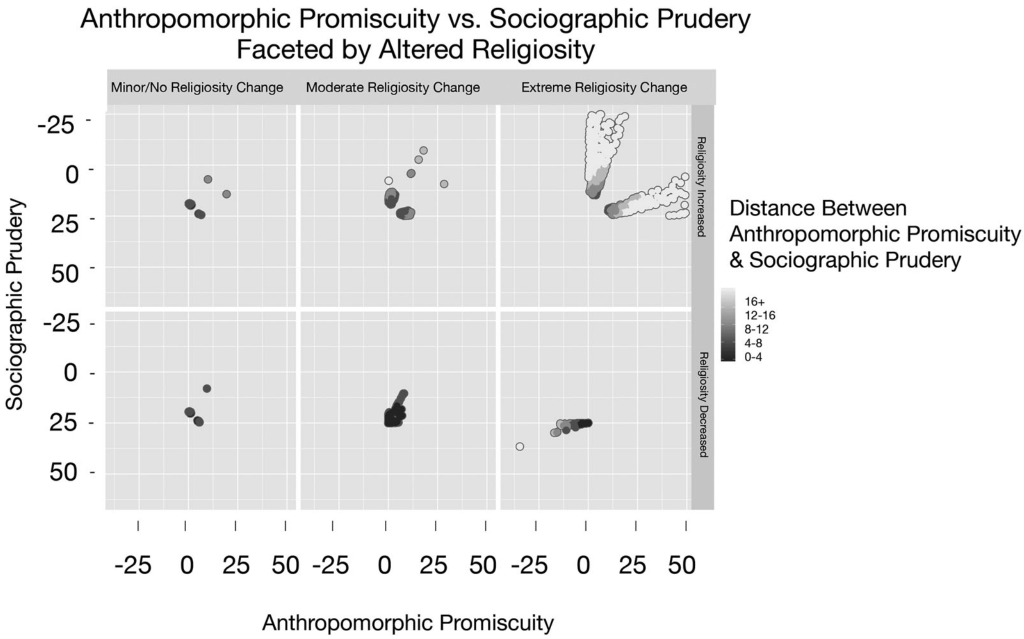

Figure 3. Anthropomorphic promiscuity, sociographic prudery, and changes in religiosity (defined as the sum of AP and SP).

Recall that our goal is to validate our claim that the mechanisms in the SDM that are purported to convert AP and SP (under certain environmental conditions) into changes in religiosity adequately reflect the literature on TMT. With this goal in mind, we can identify several important trends apparent in the model results. First, the AP and SP values are small for the majority of runs where there is a decrease in religiosity (i.e., the bottom row of Figure 3). A comparison of these three bottom facets also indicates that the decrease in religiosity goes from minor to moderate to extreme as AP and SP values decrease. Levels of religiosity are decreased the most when the AP and SP values are the lowest. The top row of Figure 3 tells a similar (albeit converse) story. Increase in religiosity goes from minor to moderate to extreme as AP and SP values get higher. These findings replicate some of the most significant results in the TMT literature outlined above, lending credibility to the causal architecture of NAHUM-SDM.

However, this validation experiment also provided insight into a couple of patterns we did not anticipate. As the distance between the AP and SP values increases, extreme changes in religiosity occur. In the upper right facet, for example, one can see that in almost all of the simulation runs where an extreme amount of religiosity is added there is a large distance (12+) between AP and SP. Similarly, in one of the simulation runs where an extreme amount of religiosity is lost (lower right facet) the difference between the AP and SP values was also large (12+). The model's disclosure of a relationship between the *distance* between these variables and *extreme increases* in religiosity raises new research questions that could be explored using laboratory experiments (or other methodologies). For example, what could we learn about the TMS by differentially measuring (or manipulating) an individual's AP and SP values?

Discussion

The NAHUM-SDM presented here is the first formal model of the dynamics discussed among scholars who study the TMS and other related systems (hazard precaution, etc.). It offers two novel contributions to this literature. First, it offers a formalized computational model that can be edited and expanded, thereby providing a way of arguing about hypotheses at a greater level of specificity than has been possible with narrative formulations of the theory. Second, it provides researchers with a new experimental tool for studying the dynamics of (and relationships between) the personal characteristics of religious individuals as they react to various environmental threats of different intensities and at different rates of occurrence.

One obvious shortcoming of the SDM approach is its focus on the mental architecture of a single, "average" individual's TMS. This does not allow us to explore the social interactions among heterogeneous individuals as they react to environmental hazards. In order to address this limitation, we also developed an ABM into which an expanded version of the TMS architecture could be incorporated. This allows for the simulation of the interaction of many religious individuals (with different personal characteristics) who relate to one another in groups as they confront the four types of threat in a shared environment.

Agent-based model

The use of multiple agents in the NAHUM-ABM architecture allows us to observe, record, and experiment on *social* dynamics that influence the TMS. The state chart in Figure 4 depicts the main rules that the agents in our model follow during any given run.[4] These rules specify how agents react personally to perceived threats as well as how they interact with other agents. Unlike the SDM, the ABM approach allows us to express both individual- and group-level considerations within a single architecture (Lane, 2014).

At the initialization of a simulation run, exactly 100 agents are assigned to one of two types (groups). Agents interact differently with same-type agents (in-group members) than they do with different-type agents (out-group members). After these type designations are in place, agents encounter various hazards: social or contagion threats associated with out-group members, and predation and natural threats associated with the environment. Agents differ in their capacity to tolerate threats, which affects the extent to which they react to such hazards. Agents whose stress is exacerbated by mortality salience will tend to cluster with other agents of the same type and intensify their performance of rituals, which helps to alleviate the stress caused by the threat. Ritual in-groups never contain agents of more than one type and are composed of agents with similar levels of religiosity (understood as the sum of AP and SP, as in the SDM, above). As agents continue their ritual engagement, their level of religiosity will tend to become more like the (averaged) religiosity of those agents with whom they have just ritually interacted. In any given run, therefore, an agent's levels of AP and SP (i.e., religiosity) change over time, which in turn affects the other agent's perception of them as viable ritual co-participants.

Variables in the ABM

Many of the variables used in NAHUM-SDM recur in NAHUM-ABM. We also added some new variables in order to capture population-level data. One new group-level variable is the ratio of the number of members in the two groups; this allows us to simulate the relationship between majority and minority groups within a population. When the group counts are 60 and 40, for example, the majority group constitutes 60% of the population. Another variable is ritual cluster size, which can be tracked as agents gather together with in-group members with a similar religiosity level to perform rituals in the face of threats. At an individual level, agents vary in their tolerance levels for – and so their susceptibility to becoming stressed by – each of the hazards (predation, contagion, natural, and social). For example, each agent architecture contains *contagion_distance* and *social_distance* variables that determine the distance at which an agent can be affected by contagion and social hazards. A *group_distance_anthropomorphic* variable indicates the maximum difference in AP levels that will determine which agents will seek each other out to perform a new ritual. A *group_distance_sociographic* variable indicates the maximum geographic distance between two agents that determines whether they can try to form ritual clusters.

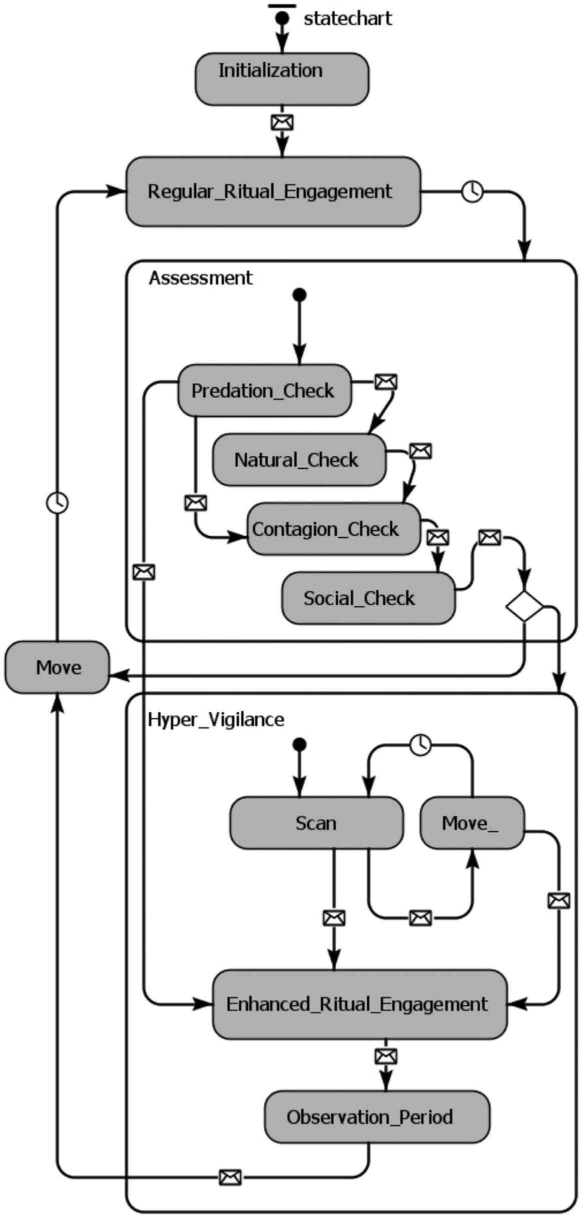

Figure 4. Key parts of the state chart diagram for NAHUM-ABM. Full details and source code may be found in the Supplementary Materials.

We used this ABM model to perform two experiments. The primary goal of the first was to replicate findings in the TMT literature, which helps to validate the causal architecture. We investigated the way in which the level of prior religiosity (with high prior religiosity, meaning a high sum of AP and SP, being a proxy for fundamentalism) affects the extent to which an individual's religiosity is maintained or increased during a simulation run. The second experiment was designed to explore the social dynamics within and across religious groups as a population encounters various environmental hazards. Here we focused on the sizes of the ritual groups that formed within the entire population during a simulation run, altering personal and contextual conditions in order to tease out relevant causal dynamics. This sort of experiment goes far beyond what is possible (for pragmatic and ethical reasons) in traditional methodologies such as psychological laboratory tests and ethnographic observation. Computer simulations avoid the logistical difficulties associated with investigating large human populations *in situ* by carrying out experiments *in silico*.

Results from ABM experiment 1

As noted above, one common finding reported in the TMT literature is that individuals with high initial religiosity rely upon their religiosity to alleviate stress to a greater extent than individuals with low initial religiosity. If the NAHUM-ABM computational architecture holds water, we would expect it to be able to replicate this sort of finding. In other words, simulated agents with a higher prior religiosity ought to experience a greater increase in religiosity (under stress) than agents with a (relatively) lower prior religiosity. Throughout a model run the level of an agent's religiosity will typically change in response to hazards but, based on the TMT literature, we would not expect an agent with extremely high religiosity to react to environmental threats in the same way as a person with low religiosity. Our hypothesis, then, was that individuals with low prior religiosity would not achieve the same levels of religiosity (at the end of a given run) as individuals who began the run with high prior religiosity (e.g., fundamentalists).

This is indeed the pattern we observed when running NAHUM-ABM. Table 2 presents the results of an experiment designed to test this hypothesis. Our goal was to capture the change in average and individual religiosity (culminating AP and SP) as a function of initial levels of religiosity (prior AP and SP). Consequently we needed to compare populations with low initial religiosity against populations with high levels of religiosity. We also varied the relative size of the majority and minority groups and the population's tolerance for hazards, ensuring that at least one natural hazard occurs during the simulation. To that end, we ran a Monte Carlo parameter variation experiment, setting the minimum of the prior AP and prior SP distributions to 1, the maximum to 10, and the mode to either 3 (low prior religiosity) or 6 (high prior religiosity); setting the percent of the minority population to 10, 25, or 40; and setting all hazard tolerance settings to either 30 (low) or 60 (high). We ran between 10 and 30 replications for each combination of these parameters seeking 95% confidence level on the average culminating AP and SP.[5] We subsequently binned the results into four ranges of prior AP and prior SP (1–3, 3–5, 5–7, 7–10).

It is important to notice that the unit of measurement used in the ABM for AP and SP is different from the SDM. The difference reflects the different modelling paradigms. Recall that the SDM does not model multiple individual agents, does not distinguish between majority and minority groups, does not allow for ritual clusters, and measures AP and SP for a single idealized and average representative of an imagined population. By contrast, the ABM tracks AP and SP for each individual agent, permitting the calculation of averages for ritual cluters, for the majority group and the minority group, for the entire population, or for other population segments. In Table 2, the values for AP and SP are averages for segments of the entire population as determined by values of prior AP and prior SP, regardless of which group agents belong to. For example, the number in the top left corner of Table 2 (2.72) is the average culminating AP for agents having initial AP between 1 and 3 across all runs of the simulation in this experiment.

Table 2. Results of Experiment 1 for NAHUM-ABM (AP and SP are measured from 1 to 10; prior AP and SP values are assigned to agents using a triangular distribution with mode that varies within the experiment; averages, minima, and maxima of culminating or end-of-run AP and SP are calculated for each subgroup indicated).

	Anthropomorphic promiscuity (AP)					Sociographic prudery (SP)			
	Prior: 1–3	Prior: 3–5	Prior: 5–7	Prior: 7–10		Prior: 1–3	Prior: 3–5	Prior: 5–7	Prior: 7–10
Avg Culm. AP	2.72	4.22	5.60	7.20	Avg Culm. SP	2.71	4.17	5.54	7.12
Min Culm. AP	1.03	1.09	1.15	3.12	Min Culm. SP	1.00	1.00	1.00	3.00
Max Culm. AP	6.73	9.06	9.19	9.17	Max Culm. SP	6.67	9.00	9.00	9.00

The individual levels of AP and SP for each agent were recorded at the end of each simulation run, along with averages for the majority and minority groups. Notice that the highest level of culminating AP or SP (measured from 1 to 10, and listed in the row labelled "Max") is extremely high for individuals with high prior AP or SP. Individuals with the lowest prior AP or SP, on the other hand, never achieve the same maximum. It is also worth noting that neither ceiling nor floor level effects are observed for high or low prior AP or SP. This may be due to the ways in which AP and SP change during ritual participation. Because agents only initiate ritual actions with those agents who are similar to themselves in AP and SP, and their post-ritual AP and SP levels are affected by their co-participants, it makes sense that there are localized transformations within the population that make ceiling and floor level effects unlikely to be observed.

Results from ABM experiment 2

The relationship between religious variables and group size in ritual activities has been a controversial issue in the scientific study of religion (Atkinson & Whitehouse, 2011; Hoverd, Atkinson, & Sibley, 2012). In order to explore the role that the TMS might play in these social dynamics in various environmental contexts, we designed an optimization experiment that searched for the conditions under which the largest ritual cluster (in a given run) is at a minimum and the conditions under which the largest ritual cluster is at a maximum. The experiment sheds light on the way in which ecological factors (e.g., the frequency of mortal predation and natural hazards) and social factors (e.g., encounters with potentially contagious or threatening out-group members) can impact the social dynamics and size of religious ritual clusters.

All of the other behavioural rules from Experiment 1 apply here as well. Recall that agents only participate in rituals with other agents who are of the same type (in-group members) and who have similar levels of religiosity; in response to threats, agents constitute ad hoc and perpetually shifting "congregations" (ritual clusters), which in turn influence the agents' AP and SP. While agent type is fixed for a given run of the simulation, ritual formations follow a stochastic process. Agents normally move through the simulation environment randomly, but when mortality salience spikes they begin to search their local area for potential in-group ritual co-participants. These aspects of the causal architecture would lead us to expect that SP in particular would increase (at different rates depending on prior religiosity) as an agent encounters out-group members (potential social threats). Agents whose type is a "minority" are more likely to encounter agents of the other type (the "majority"), and so we would also expect that the SP (and religiosity in general, which here means the sum of AP and SP) of the minority group would be more likely to increase.

The results of this experiment are presented in Table 3. The first column lists the variables. The next two columns show the minimum and maximum possible settings for each variable. The fourth column records the model parameter values under which the size of the largest ritual cluster that appears during the 1,000 time steps of the simulation is maximized. The fifth column records the model parameter values under which the size of the largest ritual cluster is minimized (no fewer than two agents). The parameter space consists of over 97 billion possible combinations of input values.

All of the variables (except the last one in Table 3) represent minima, maxima, or modes. These are used to initialize the triangular distributions of the respective variables. The minimum and maximum represent the lower and upper bounds of the distribution. The mode represents the most likely value in the distribution, which can (in principle) vary between the minimum and maximum values. The optimization experiment helped us identify the distribution settings that maximize the size of the largest ritual cluster and the distribution settings that minimize the size of the largest ritual cluster. We consider these convenient proxies for relatively large and relatively small ritual clusters, respectively.

The conditions that minimize ritual cluster size are informative. When neither of the two types of agents constitutes an overwhelming majority of the total population (as measured by the ratio of type

Table 3. Results of NAHUM-ABM Experiment 2.

Variable	Minimum value	Maximum value	Value maximizing largest ritual group size	Value minimizing largest ritual group size
percent_of_pop_in_group_1/group_2	**0**	**100**	**1/99**	**51/49**
prior_sociographic_prudery_min	1	10	1	1
prior_sociographic_prudery_max	1	10	10	10
prior_sociographic_prudery_mode*	**1**	**10**	**9**	**4**
prior_anthropomorphic_promiscuity_min	1	10	1	1
prior_anthropomorphic_promiscuity_max	1	10	10	10
prior_anthropomorphic_promiscuity_mode^	**1**	**10**	**8**	**9**
contagion_tolerance_min	0	100	0	0
contagion_tolerance_max	0	100	100	100
contagion_tolerance_mode*	**0**	**100**	**20**	**60**
social_tolerance_min	0	100	0	0
social_tolerance_max	0	100	100	100
social_tolerance_mode*	**0**	**100**	**90**	**100**
predation_tolerance_min	0	100	0	0
predation_tolerance_max	0	100	100	100
predation_tolerance_mode^	**0**	**100**	**10**	**30**
natural_tolerance_min	0	100	0	0
natural_tolerance_max	0	100	100	100
natural_tolerance_mode	0	100	0	0
contagion_probability_min	0	100	0	0
contagion_probability_max	0	100	100	100
contagion_probability_mode*	**0**	**100**	**80**	**50**
predation_probability_min	0	100	0	0
predation_probability_max	0	100	100	100
predation_probability_mode	0	100	100	100
social_probability_min	0	100	0	0
social_probability_max	0	100	100	100
social_probability_mode	0	100	50	50
chance_for_natural_hazard_to_occur^	**0**	**100**	**51**	**31**

Notes: Bold items in the table indicate cases in which there was a difference between the parameter values that maximize and minimize the largest ritual-group size, highlighting those parameters on which ritual-group size most depend. Within the bold items, asterisks (*) and carats (^) indicate those variables that most directly impact SP and AP, respectively.

1 to type 2 agents on the first row of the table body), and when the environment is more densely populated with heterogeneous agents (as measured by a distribution mode somewhere near the middle of the range), ritual clusters tend to be smaller. This is best exemplified by the difference between the distributions associated with *prior_sociographic_prudery*. Initializing a population with a *prior_sociographic_prudery_mode* of 9 produces a relatively homogenous population; in the experiment, this yielded the largest ritual cluster sizes. By contrast, when *prior_sociographic_prudery_mode* is set at 4, the population is more evenly distributed throughout the possible space of values for sociographic prudery. The smallest ritual clusters are observed when the population has this relatively high heterogeneity. Smaller ritual clusters also form when there are lower probabilities of natural hazards and a higher average tolerance for out-group members (*social_tolerance_mode*), predation (*predation_tolerance_mode*), and contagions (*contagion_tolerance_mode*). This suggests that heterogeneous populations with high average hazard tolerance produce smaller ritual clusters, whereas homogenous populations with low tolerance levels are more likely to form large ritual clusters.

The relationship between AP, SP, and religiosity change in NAHUM-ABM

As an additional validation mechanism for the ABM, we explored the impact of various combinations of AP and SP on changes in religiosity and group size (i.e., size of majority versus minority groups, not size of ritual clusters). In what follows, it is important to keep in mind the key differences between the SDM explored above and the ABM. The latter models the social interaction of many different agents, whose behaviour is shaped by the coexistence of minority and majority group members. These kinds of dynamics are not representable in an SDM.

We explored the ABM by sweeping the parameter space, running the simulation more than 150,000 times with different combinations of input parameters. At the conclusion of each simulation run, we recorded the average culminating AP, average culminating SP, and average increase in religiosity (i.e., the sum of the increase from prior AP to ending AP, and the increase from prior SP to ending SP) for the majority and minority populations. Each combination of input parameters was replicated between 2 and 10 times (depending on how long it took to obtain a confidence level of 95% for culminating AP and SP at the end of each run) in order to ensure that the values obtained for religiosity are 95% likely to be caused by the values of the input parameters (including group size) and not a result of chance. It is important to note that the calculations are such that, though AP and SP can go up and down for a given agent, ritual participation can never drive AP and SP below their initialized values (prior AP and prior SP). Thus, we only need to analyse increases in religiosity.

Each of these values forms a single point in Figure 5. Plotting these points together can help us discover relationships among size of majority and minority groups; culminating AP and SP; and minor, moderate, and extreme increases in religiosity. The *x*-axis and *y*-axis in Figure 5 indicate the range of values recorded in our simulation runs for the average of culminating AP and SP, respectively, where the average is taken over agents in the six facets displayed. Both axes run from 2.5 to 7.5. It is important to note that these axes are different from those used in Figure 3. The difference reflects the difference in modelling paradigms used. The SDM does not model individual agents in majority and minority groups; rather, AP and SP are the religiosity values for an idealized agent reacting to threats. By contrast, the ABM models individual agents in majority and minority groups, so the axes in Figure 5 reflect the average culminating AP and SP for agents in the majority and minority groups, faceted by the size of religiosity increase.

The top row of Figure 5 represents combinations of culminating AP and SP corresponding to increased religiosity for individuals in the minority population. The bottom row represents those combinations corresponding to increased religiosity for individuals in the majority population.

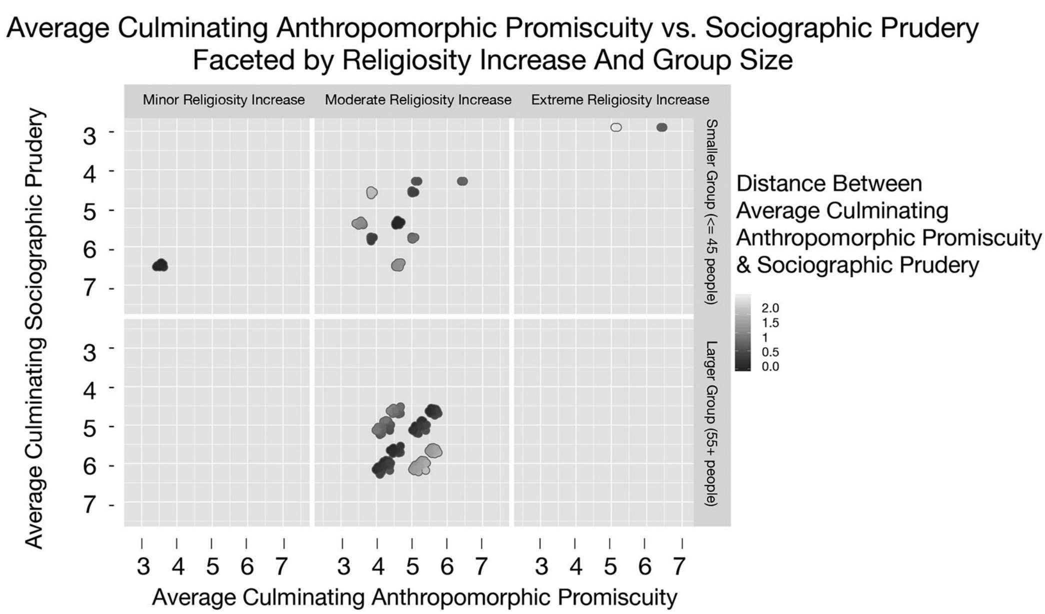

Figure 5. Average culminating (i.e., final, end-of-run) AP versus SP faceted by altered religiosity (the sum of culminating AP and SP relative to the sum of initial or prior AP and SP) and group size (with minority group in the top row and majority group in the bottom row) when majority group exceeds minority group by at least ten agents.

The left, middle, and right columns represent minor (0–4), moderate (4–7), and extreme (7–10) increases in religiosity, respectively. The shading of the coloured points in Figure 5 is determined by the *distance* between the AP and SP values recorded within a (minority or majority) population for a given simulation run. Darker values represent smaller distances (0.0–0.5), grey values represent moderate distances (1.0–1.5), and lighter values represent large differences (>1.5). This differentiated shading did not reveal as strong a trend as it did in the SDM (Figure 3). In the ABM (Figure 5) there are only two points with a large distance between culminating AP and SP (the light circles in the upper right facet). These points produced an extreme increase in religiosity, but so did two other points (in the same facet) with only a medium difference between culminating AP and SP.

Several trends become apparent from this presentation of the data. Reading the top row of the graphic from left to right, one can see that the average culminating AP and SP values in the minority population increase as the average increase in religiosity moves from minor to moderate to extreme. Reading across the bottom row, however, one can see that the majority population only ever achieves moderate increases in religiosity. These moderate increases are caused by moderate values (4–6) of culminating AP and SP. Comparing the two rows, it becomes clear that minor and extreme increases in religiosity only occur in the minority population.

One possible part-explanation for this difference is that there is more volatility in the (average) culminating AP and SP values of a minority group because the changes caused by different model parameterizations are magnified within a smaller population. In such populations, higher (>6) and lower (<4) average AP and SP values occur more frequently, which create minor and extreme increases in religiosity, respectively. In a majority group, by contrast, higher and lower average AP and SP values do not occur as often because the effects of parameterization changes are spread out across more people. In such populations, the average value of culminating AP and SP tends to stay in the moderate range (4–6) across simulation runs, producing only moderate increases in religiosity.

General discussion

Our NAHUM simulations represent the first attempt to apply computer modelling techniques to the study of terror management. The NAHUM-SDM experiment explored ways in which an individual's personality traits can shape reactions to life-threatening environmental stimuli and alter his or her religiosity over time. The NAHUM-ABM experiments explored the role of mortality salience in the social interaction of heterogeneous religious individuals who intensify their ritual engagement in response to environmental hazards. We believe that the plausibility of the causal architectures we constructed to guide our models is supported by their capacity to replicate the findings of other TMT researchers. Their capacity to generate new insights into the relationships among group size, hazard tolerance, and religiosity also highlights the research potential of computer models that can investigate both cognitive and coalitional dimensions of "religion" within simulated environments.

As with any computer model, both NAHUM simulations are limited. We only included the variables we believed were necessary to construct causal architectures that could capture the sort of religious dynamics and behaviours we were most interested in exploring (and explaining). There are important findings in the TMT literature that are not captured by our models. For example, the meta-analysis included in this volume (Jong et al., in press) describes a curvilinear relationship between religiosity and mortality salience that is commonly detected in TMT studies using psychological experimentation. Developing a computer model that could replicate this finding would require agents with extremely low (or no) religiosity, as well as the capacity to differentiate between the utilization of religious and secular worldviews in the management of terror.

Despite these limitations, we believe that the NAHUM simulations offer several significant contributions to the growing literature on religiosity and terror in general, and TMT in particular. Most importantly, perhaps, they introduce a new way of "experimenting" with the causal dynamics of terror management. Direct experimental tests of the buffering effects of religious belief on death anxiety are relatively rare; computer modelling can complement laboratory experiments (and other methodologies) by providing a way to explore regimes of behaviour that otherwise could not be studied.

Moreover, such techniques make it possible for researchers to explore the different environmental conditions under which various religious behaviours are likely to be produced. Another article in this issue (Vail, Arndt, Abdollahi, & Sheldon, in press) helpfully analyses the different impact of mortality salience on the sense of meaning in life among Christians and atheists. As these authors note, however, their approach is limited by its lack of cross-cultural data. One recent study has provided evidence that ecological triggers and cognitive capacities are both factors that constrain the dominance of precautionary themes in general (across cultures), as well as conditioning the variation found between cultures. South Africans, for example, tend to be more worried about predation and depletion of resources than inhabitants of Britain (Mort, Fux, & Lawson, 2015). This suggests that environmental differences play an important role in the interaction between mortality salience and religiosity. The NAHUM simulations allow researchers to "experiment" within a simulated environment, i.e., to explore ways in which different types and frequencies of contextual hazards affect the cognitive and coalitional variables of religious agents. Such approaches can generate novel hypotheses that can then be validated through the analysis of existing datasets or laboratory experimentation.

The formalization of the theory into a computationally executable form can help researchers identify the limits of TMT itself, and find points of contact with other theories. We invite other scholars to contest our formalizations and claims about the causal architecture, hoping that this process itself will bring added clarity (and creativity) to the ongoing debates over the relation between religion and terror. We see several possibilities for future research. Both of the NAHUM simulations are ripe for additional exploration, and can be extended or adapted as new empirical studies help to refine TMT. Our own plans include the incorporation of semantic analysis methodologies within the ABM, which we hope will enable us to simulate the ways in which different worldviews play a role in agents' attempts to alleviate terror and moderate the effects of mortality salience. We are also in the process of developing new models that integrate other theories, which we plan to link to the NAHUM causal architectures described here. This is yet one more way to enrich the interdisciplinary discussion around TMT.

Notes

1. These different ways of describing M&S as a research technique are probably complementary. We regard the third of four paradigms (computational approaches) as already requiring rich interactions with theory and empirical data to be scientifically useful, so we are happiest describing what we are doing here as the "third pillar" or "third paradigm." The fourth paradigm is reliant upon statistical associations in data sets so we find it insufficient for our current purpose, which is to provide a theoretically grounded model that can engage with falsifiable and repeatable empirical studies. But the architecture presented here can also provide a basis for statistical modelling compatible with a "big-data" analytic approach should relevant data become available; that would be "fourth paradigm" work.
2. The terms "anthropomorphic promiscuity" (AP) and "sociographic prudery" (SP) are borrowed from Shults's exposition and analysis of empirical findings and theoretical developments that support these claims (Shults, 2014, 2015). In those contexts, these phrases are part of a broader argument which plays on the metaphor of "bearing gods" (supernatural agents are "born" in human minds and "borne" in human coalitions). AP includes within its scope other terms that are more widely used in the literature, such as hypersensitive agency detection, teleonomic reasoning, ontological confusion, and theory of mind. Likewise, SP includes within its scope more familiar terms such as in-group bonding, out-group vigilance, parochial altruism, and coalition building. The key advantage of employing the novel phrases AP and SP here is that we can control their definitions, focusing on behavioural features of human life, rather than on specific cognitive and social mechanisms, while simultaneously relating them to a wide range of existing research results.
3. The acronym is also intended as an allusion to the Old Testament prophet Nahum, who responded to the threat of Nineveh against his religious in-group (Judah) by articulating his vision of an "avenging and wrathful" (1:2) supernatural agent who promises that He will protect Judah, and urging them to fulfil their vows and celebrate

their rituals (1:15). Nahum prophesied that the god of Judah would shame the Ninevites by "lifting up their skirts" and "throwing filth at them" (3:5–6), reminding them that "even the infants" of that god's former enemies were dashed to pieces in the streets (3:10). Happily not everyone reacts to mortality salience as violently as Nahum did, but he does provide an excellent illustration of the way in which terror can activate the detection of (and promote ritual engagement with) hidden intentional forces that are imagined to be watching over one's in-group.

4. This architecture is constructed in a "modular" fashion, which makes it easier to understand the model and observe its component parts. It also allows this architecture to be incorporated in whole or in part into more complex models with minimal revision, which promotes more efficient validation. This approach does not reflect a pre-existing commitment to the view that modular theories of cognition are more biologically plausible. Given the current state of cognitive neuroscience, most claims about the relationship between neurophysiological structures and cognitive functions are impossible to validate. Future research will incorporate domain-general functions, such as associative learning, with this modular approach to strengthen the architecture as well as broaden its potential capabilities.
5. Note that the simulation engine runs the minimum number of replications for a solution and stops evaluating a solution if (1) the inferred true value is within a given range (in this case, 5%) of the mean of the replications performed so far, (2) the current replication is not converging, or (3) the maximum number of replications has been run. In the second and third cases, the corresponding parameter combinations are discarded.

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