Trends in Cognitive Sciences

CellPress

Review

Cognitive computations underlying ritual performance and persistence

Martin Lang [1,*], Khatereh Borhani [1], Alexandra Ružičková [1], Eva Kundtová Klocová [1], and Radim Chvaja [2]

From petitionary prayers to pilgrimages, rituals are found in every known culture. Yet, the reason for their persistence is a matter of active debate. Some studies portray rituals as attempts to affect uncertain outcomes, whereas others emphasize their role in facilitating social cohesion. We review the cognitive processes underlying both perspectives and draw on advances in reinforcement learning to integrate them. Specifically, ritual participation is motivated by two processes: habitual reinforcement of affective and social rewards experienced during performance (model-free learning) and reinforcement of pragmatic and cooperative benefits derived from culturally shared world models (model-based learning). This framework synthesizes previous accounts and illuminates ritual's role in sustaining intersubjectively aligned world models in past and present societies.

Highlights

Recent computational work shows that rituals can be analyzed through reinforcement learning architectures, with both model-free and model-based mechanisms shaping their acquisition and persistence.

Culturally transmitted world models supply strong priors over ritual action–outcome relations, enabling model-based counterfactual simulation and Bayesian updating, while making ritual beliefs resistant to disconfirmation from weak or ambiguous evidence.

Ritual behavior is sustained through a combination of model-free affective and social reward signals, as well as model-based predictions about pragmatic and social outcomes encoded in the cultural world model.

By linking shared norms to supernatural and social consequences, religious rituals create mutually reinforcing value structures that stabilize normative behavior across generations.

The puzzle of ritual persistence

Rituals are an essential part of human life. We celebrate birthdays, sing national anthems, knock on wood, say grace, attend weddings and funerals, honor ancestors, and collectively pray to gods. During the lockdowns associated with the early stages of the COVID-19 pandemic, restrictions on collective practices, such as attending mass or holding funerals, amplified the pandemic's toll on mental health [1]. Intriguingly, some rituals are also remarkably costly: people undertake on-foot pilgrimages spanning hundreds of kilometers, pierce or scarify their bodies, or walk barefoot across burning coals. Given that rituals are found in all known societies, earning them the label of a cultural universal [2], understanding the cognitive processes that underlie the motivation to perform them is key to explaining their persistence (Box 1).

While people describe a wide range of reasons for performing rituals, most reasons appeal to social identity: this is what we do, what has always been done in our community, what our parents and grandparents did before us [9]. In this sense, rituals are immensely meaningful social acts that define groups, strengthen communal bonds, and perpetuate cultural identities [10]. However, rituals are also enacted individually for pragmatic ends: to avert harm, restore health, or secure good fortune [11,12].

These two categories of folk explanations of ritual persistance are reflected in the main cognitive theories of ritual. Social-function accounts emphasize how rituals promote social norms and group cohesion via mechanisms of social bonding [13–15] and commitment signaling [16,17]. By contrast, error-management and instrumental accounts treat rituals as by-products of attempts to intervene in the world under limited control [18–21] and to regulate anxiety [18,22].

At first glance, these explanations appeal to different reasons for ritual persistence (social bonding vs. world intervention). Yet these perspectives are not mutually exclusive; rather, they intertwine in important ways. Pragmatic and social motivations can become functionally coupled, since both

[1]LEVYNA: Laboratory for the Experimental Research of Religion, Masaryk University, Brno, Czechia
[2]Faculty of Economics, European Research University, Ostrava, Czechia

*Correspondence: martinlang@mail.muni.cz (M. Lang).

Box 1. What are rituals?

Rituals, like any broad phenomenon that permeates the lives of billions across the world, are notoriously difficult to define. Decades of anthropological, sociological, and psychological research, however, converge on several core features: rituals are performative, structured, and formalized acts, marked by rigidity, and often performed collectively according to a group's tradition [3–6]. Take, for example, a Sunni Muslim prayer (ṣalāt), which is *performed* five times a day at prescribed times. Each prayer follows a *fixed sequence* of bodily movements and recitations oriented toward the Kaaba. The act is highly *formalized*, where prescribed movements and utterances allow minimal individual variation. But the rationale for this specific form is often missing, and rarely includes an explicit causal explanation for why the ritual must be performed that way. When provided, such explanations typically invoke symbolic meanings or the reenactment of mythological events. Thus, unlike ordinary habits, ritual actions are typically (i) causally opaque, (ii) normatively prescribed, and (iii) embedded in shared symbolic world models.

While ritual is often associated with religion, it represents a general class of behaviors that also appear in secular contexts: be it a presidential inauguration, the Māori haka performed pre-match by the All Blacks rugby team, or idiosyncratic rituals related to everyday actions. At the same time, ritualization as a cognitive-behavioral pattern has been linked to certain psychopathological conditions such as obsessive compulsive disorder, in which the pathological ritualization (i.e., rigid formalization and stereotypization) of everyday activities constitutes one of the core defining features [7,8].

Notice that all of these examples share an emphasis on the repetitive execution of actions within rigid structures that are rarely altered, without necessarily understanding why that needs to be so. This continuity from cultural to pathological rituals illustrates that the ritualization of behavior is a natural and pervasive tendency across both individual and collective domains of human life, which may have important functions. Yet, as we show later, rituals, and especially religious rituals, further add a symbolic layer to ritualization, which adds important motivation for ritual performance.

depend on learning ritual value from feedback resulting from experienced action–outcome contingencies, and the positive value of one may help sustain the other.

Recent advances in reinforcement learning theories [23] and their implementation in naturalistic settings [24] provide a formal language for describing these feedback dynamics. As we will summarize in this review, in both pragmatic and social contexts, individuals revise their expectations about ritual value based on culturally transmitted information and experienced pragmatic and social benefits. These integrated benefits give rise to stable patterns of ritual motivation, even when ritual outcomes are uncertain or difficult to verify.

Spurious associations, causal opaqueness, and anxiety

The proponents of rituals as pragmatic means to avoid misfortune and achieve desirable outcomes point out that rituals often occur in situations characterized by limited instrumental control. For example, the onset of COVID-19 was associated with a global surge in Google searches for prayer [25], and laboratory and field studies show that students, athletes, and gamblers report performing rituals more frequently before difficult or uncertain tasks [26,27]. Why are rituals so compelling when instrumental control is lacking?

In highly uncontrollable situations, people's drive to reduce uncertainty can still motivate action, even when clear instrumental solutions are unavailable [3]. Although this tendency likely varies across individuals and contexts [28], formalized rituals often emerge as a class of behaviors that help regain control [29,30] and become reinforced through two distinct processes: enhanced detection of action–outcome contingencies and anxiety management.

Rituals as spurious associations

Under conditions of uncertainty, individuals increase their sensitivity to potential action–outcome contingencies [31], engaging in behaviors aimed at improving predictive control over the desired outcome. Because such outcomes may occur by chance following ritual performance, heightened contingency detection can generate **spurious action–outcome associations**

Glossary

Bayesian updating: people hold internal beliefs about the causal structure of the world, which serve to generate hypotheses about the state of the world and how an action might help transition into a different state. When a hypothesis is confirmed (e.g., prayer leads to safety), the supporting evidence increases the probabilistic weight of that world model (posterior belief).
Causal opacity: the absence of a clear mechanistic understanding to determine how an action produces its intended outcome, making it difficult to identify which elements of the action do the causal work.
Costly signals: effortful communication of a hidden trait that cannot be directly observed. By attaching a cost to signal production (e.g., painful ritual performances), signals become more reliable, as only those with genuine intentions are willing to bear the cost.
Eligibility traces: a mechanism in reinforcement learning that allows recently performed actions to be eligible for receiving credit when feedback arrives later. Eligibility traces allow reward prediction errors to strengthen not only the most recent action but also earlier actions in a sequence, thereby supporting learning over temporally extended behaviors.
Internalization: a process of incorporating external norms, values, or beliefs into one's own world model. These originally external norms and values then motivate behavior, even without external enforcement.
Inverse reinforcement learning: learning about the rewards that guide others' behavior by observing their actions, thereby inferring not only what to do but also which outcomes are valued in a given environment.
Model-based learning: learning based on an explicit representation of state transitions and associated rewards. Decisions rely on inferring which actions are most likely to produce a desired outcome.
Model-free learning: learning based on previously reinforced action values without representing how the environment is structured. Decisions rely on choosing the action with the highest expected value.
Reward-prediction error: the discrepancy between expected and actual outcomes. Its valence and

(see Glossary) that can become reinforced over time. This dynamic reflects well-established trial-and-error learning principles originally posited by Thorndike [32] and later developed by Skinner as operant conditioning [33].

The key mechanism facilitating these spurious associations is **reward-prediction error** [34]: when a desired outcome (e.g., passing an exam or winning a competition) happens to follow a ritual action, the unexpected positive reward reinforces the value of the ritual action in the given state (e.g., before an exam). As a result, when individuals later encounter a similar state, the ritual action carries an updated value and, therefore, a higher probability of being selected again.

Computationally, this corresponds to the use of **eligibility traces** (as in **SARSA**(λ); [23]) that assign credit to earlier actions by temporal proximity. That is, in naturally unfolding state–action sequences (e.g., illness → ritual act → recovery), such temporal-difference learning allows the prediction error to propagate backward through the recently visited states and actions, so that state–action pairs that occur close to or frequently co-occur with, positive outcomes receive more credit. Note that such learning does not necessarily require reaching the outcome (e.g., afterlife salvation), only actions that are perceived to move individuals closer to the outcome, thereby producing positive prediction error.

The reliance on temporal or spatial contiguity as a cue for inferring action–outcome relationships is part of an adaptive learning strategy, as articulated in the literature on the evolution of superstitious behavior [21,35]. At the proximate level, learning under stochastic feedback can generate spurious action–outcome associations. From the ultimate perspective, though, it can be adaptive to err on the side of detecting false action–outcome links rather than missing a genuine one [20]. This is true especially when a mechanistic understanding is difficult or costly [36], when causal reasoning is still developing [37,38], or when people face high-stakes situations beyond their control [27]. From this perspective, rituals are reinforced because they mimic effective instrumental actions, which are, on average, adaptive [39].

Importantly, the reinforcement theory predicts that people will be sensitive to how demanding rituals are compared to the desired outcome. Because painful or effortful ritual acts carry an intrinsic negative reward, they will only be reinforced when they are followed by sufficiently positive outcomes to produce a net positive prediction error [40]. This cost-benefit calibration framework can help explain why some rituals remain highly costly: for example, demanding rituals are often associated with highly valued outcomes, such as the alleviation of chronic illness [41], whereas minor goals, such as passing an exam, are typically associated with less demanding rituals, like brief prayers [27].

Beyond cost-benefit calibration, reinforcement dynamics under limited instrumental control also help explain why rituals are rigid. Unlike ordinary actions, where procedural variation is functionally equivalent (e.g., holding a morning coffee in either hand), ritual actions often rigidly adhere to prescribed movements and utterances (e.g., holding sacramental wine in the right hand). Since the causal relationship between the ritual actions and the intended outcome is spurious, causal mechanics remain unclear to participants who, therefore, tend to repeat the full prescribed action. The lack of understanding of the causal chain underlying ritual efficacy is often described as **causal opacity** [4,42].

Under conditions of causal opacity, the reinforcement learning mechanism updates the value of the entire sequence of actions that were associated with a positive reward prediction error. Thus, the whole action sequence needs to be repeated, ensuring that none of the potentially

magnitude update future action values: positive errors increase an action's value, while negative errors decrease it.
SARSA (State–Action–Reward–State–Action): an on-policy reinforcement learning algorithm that updates the value of an action based on the reward received and the next action actually taken by the agent under the current policy.
Shared model of the world: a collectively held representation of how the world works, including its causal structure, norms, and values, which enables co-ordination, prediction, and mutual understanding within a group.
Spurious action–outcome associations: perceived links between an action and an outcome that are not supported by a true causal relationship. Such associations can form when a desired outcome happens close in time to the action, leading the action to acquire value despite lacking objective efficacy.

efficacious elements are omitted [39]. In support of this view, rituals are parsed and executed at a much finer level of granularity than ordinary instrumental actions [43,44].

Rituals regulate anxiety

Ritual performance can also engage affective computations, especially in downregulating anxiety, which, in turn, may reinforce the value of the ritual. For example, a predictive-processing account of ritualization [22] suggests that the rigid structure of rituals makes them well specified and easily anticipated. This predictability may be particularly beneficial in uncertain states: performing a familiar ritual (e.g., prayer), where each step unfolds in an expected sequence, can increase the feeling of control over the situation, thereby lowering anxiety [45–47].

Furthermore, some rituals may have substantial working-memory demands because participants must continuously monitor fine-grained motor parameters of their performance to ensure they perform the ritual according to the predefined script. The hazard-precaution theory of rituals stipulates that cognitively demanding ritual performance shifts attention away from the threat and toward the precision of performance, thereby attenuating anxiety [3,48]. In contrast to the predictive-processing explanation outlined above, this account assumes that ritual performance is not habitual or easily predictable and instead requires considerable cognitive resources.

A direct comparison of the predictive-processing and hazard-precaution approaches found stronger support for the former one [45], and rituals performed in anxiogenic situations (e.g., sports competitions or exams) generally rely on well-rehearsed, habitual routines rather than complex, cognitively demanding sequences [27]. Either way, a reduction in anxiety following the ritual action functions as a positive reward signal that updates the value of that action. Over time, such internally generated reward-prediction errors can stabilize ritual behavior and sustain its persistence even when the ritual yields no desired intervention in the real world (Figure 1).

The challenge of creating and maintaining group identity, norms, and commitment

In contrast to the spurious association account, the social-bonding account of ritual emphasizes the social function of ritual. Indeed, as Émile Durkheim theorized more than a century ago, rituals embody a community's abstract norms and values, binding individuals into a single moral entity [49]. Following these initial insights, ritual theoreticians suggested that rituals constitute a collective communicative system through which individuals signal their commitment to shared norms and values, mutually reaffirm them, and ensure their continuity [16].

Rituals communicate commitment

Treating ritual as a communicative act helps explain several of its characteristic features (Box 1). First, rituals need to be *performed* so that others can observe the information being conveyed. Second, the ritual structure is *rigid* so that the message is intelligible and unambiguous. Finally, within this rigid structure, there is individual *variation in performance*, which allows individuals to express their intentions and adherence to the community's normative system [5,16,17]. Why is ritual communication critical to social living?

Human groups exhibit extraordinary levels of cooperation relative to other socially living species, which is particularly striking given the low levels of genetic relatedness within such groups [50]. Yet, this low genetic relatedness implies a conflict of interest, and individuals must estimate the reliability of others' cooperative intentions while avoiding exploitation by potential free-riders.

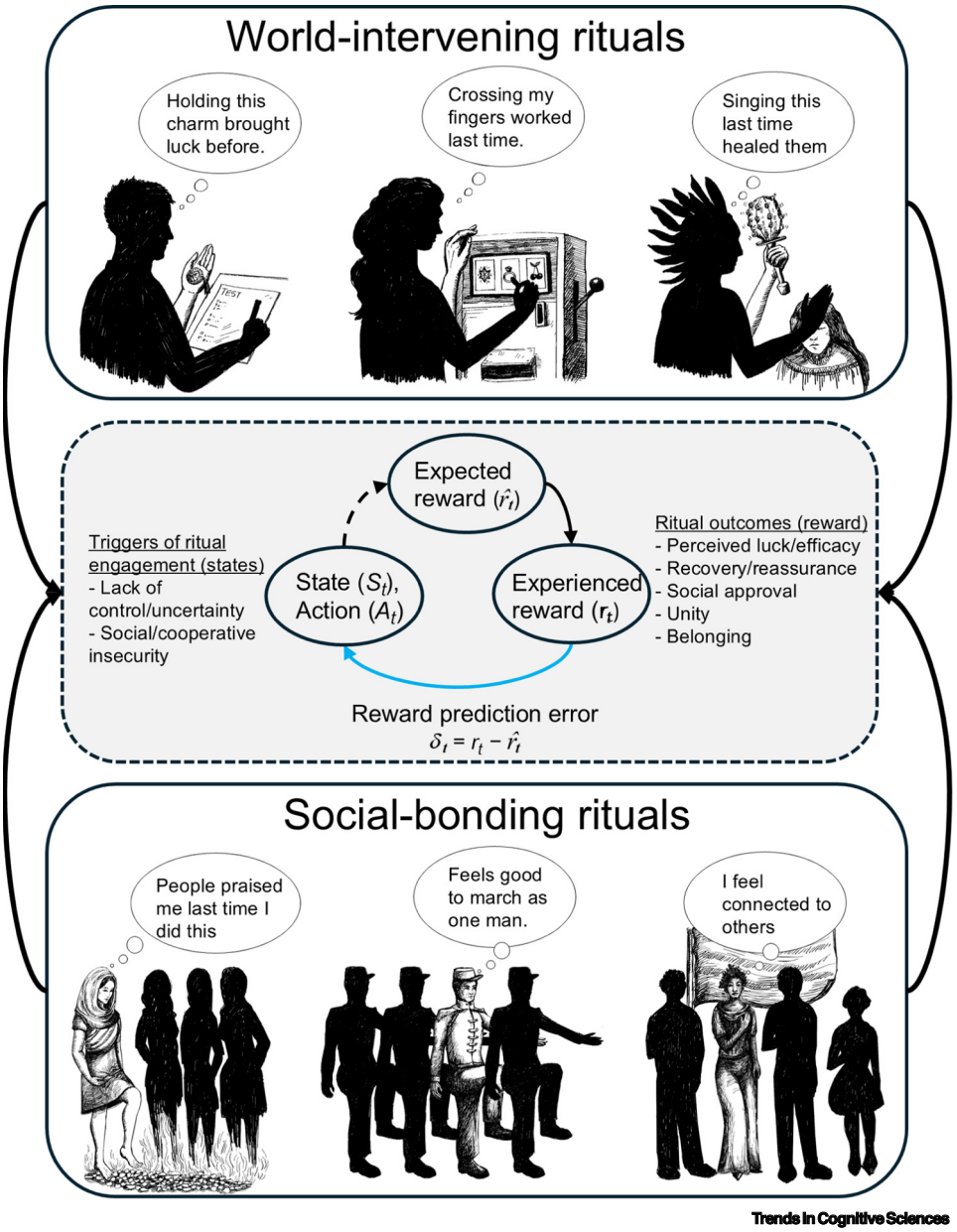

Figure 1. Reinforcement learning mechanism underlying value updating for both world-intervening and social-bonding rituals. For example, before an exam (S_t), a student performs a prayer (A_t) expecting moderate benefit ($r_t = 5$). If the exam goes well and the experienced reward is higher than expected ($r_t = 8$), a positive reward prediction error is generated ($\delta_t = 3$), increasing the estimated value of this action in the future $Q_{t+1}(S_t, A_t)$. Conversely, if the outcome is worse than expected (e.g., $r_t = 2$), the negative prediction error decreases the action value, reducing the probability that the ritual will be selected in similar future contexts.

Rituals provide a mechanism for solving this problem by reliably indicating commitment to group norms regulating cooperation: typically, only committed members are willing to spend time and energy performing rituals. From this perspective, collective ritual performance can be understood as a **costly signal** of commitment that assorts cooperators and deters free-riders [51,52], with

the ritual cost scaling from very cheap/not costly (e.g., simple prayer) to extremely demanding (e.g., participation in a life-threatening ritual) based on the need for the diagnosticity of the ritual (how important it is to exclude free-riders).

From a computational perspective, ritually signaling commitment can be reinforced through directly experienced social rewards, such as receiving praise, invitations to cooperate, or preferential treatment from others [53–55], which may scale with increasing difficulty of rituals, strengthening the cached value of performing the ritual despite its difficulty. Indeed, many practitioners voluntarily undergo painful ordeals year after year [41].

However, if rituals serve communicative functions, it may seem puzzling that they are frequently performed alone. One answer to this puzzle might be that socially prescribed rituals communicate commitment to the ritual practitioners themselves via self-signaling; that is, performers infer and strengthen their beliefs by observing their own repeated costly behavior [17,56]. Another answer might be that private ritual performance is never truly private, as it often leaves observable traces that others can judge or can be observed during collective performance (e.g., how well one memorized the Torah).

Rituals bond people together

Rituals not only communicate cooperative intentions but also directly modulate affective relationships with the group and its members. First, rituals often involve behavioral synchrony, which is defined as moving, singing, or chanting in unison. Synchrony has been shown to increase perceived similarity, blur boundaries between self and others, and facilitate interpersonal liking [57–60].

Many rituals are also profoundly enjoyable [61], especially if they involve dancing and singing, which may trigger euphoria and joy and increase interpersonal bonding [62–64]. These affective states are often synchronized between ritual participants and spectators [65–68], further boosting social bonding and mutual support [69,70]. Through such affective feedback, ritual participation generates intrinsic rewards that further reinforce its subjective value.

Moreover, intense rituals involving fire-walking, trance states, or scarification forge deep emotional memories and reinforce the fusion of identities between the self and the group [14]. When such experiences are repeatedly followed by positive social outcomes, these outcomes act as rewarding feedback that reinforces the value of participating in these demanding rituals.

Rituals reinforce a shared model of the world

While the review of cognitive processes motivating ritual performance reveals distinct channels for computing ritual value, these mechanisms individually are insufficient to explain the cross-cultural ubiquity and persistence of ritual behavior. World-intervening rituals may enhance perceived control and alleviate anxiety, yet they are likely to be unstable, as their perceived value depends on idiosyncratic reinforcement rather than systematic benefits. Conversely, social bonding can serve important cooperative functions by signaling commitment or fostering cohesion via shared bonding experiences, but such a cooperative function is inherently susceptible to free-riding because cooperative signals can be faked when incentives are large enough. We discuss how these issues might be resolved by integrating both explanations within a single computational framework.

Model-free versus model-based learning

Two computational processes are central to understanding how ritual value is reinforced: model-free and **model-based learning** [23,71,72]. Model-free learning is akin to the reinforcement

learning principles described above, where actions that have previously been followed by positive prediction errors increase in cached value (and vice versa for punishment). Model-based learning, on the other hand, relies on internal representations of states, possible actions, expected rewards, and transition probabilities between states. While model-based learning is more computationally demanding, as it relies on an internal model of the world, this world model affords simulating and evaluating alternative courses of action (and their consequences) before acting.

For instance, in chess, a model-free player learns to play openings that previously led to wins without being able to explain why, whereas a model-based player mentally simulates gameplay several moves ahead to evaluate the likely consequences of each decision (e.g., the probability of transition to states associated with reward). Applying these insights to ritual, it has been argued that ritual emphasis on action is symptomatic of model-free learning [73]. Indeed, in most cultures, children actively participate in rituals, and such participation is strongly socially reinforced: children receive praise, attention, and encouragement for faithfully reproducing ritual actions without necessarily understanding those actions [15].

However, rituals are not merely random, conventional actions that are aberrantly and socially reinforced; they also embody and enact the community's **shared model of the world** [74]. That is, they represent culturally transmitted ideas about how the world works, what forces govern events, and what actions are appropriate or efficacious within that ontological framework [5,13]. Many rituals explicitly teach the community's world model through storytelling and performance, anchoring this abstract model in culturally salient symbols such as the national flag, the totem, or the cross. By emotionally charging these symbols [75], rituals make abstract norms tangible [76,77] and facilitate the socialization and **internalization** of the particular world model.

Since such culturally acquired world models are generative, they enable counterfactual inference over transitions between states given alternative actions ('what would happen if…') [78,79]. In an abstract scenario, the agent begins with priors over transition probabilities (given state S_t and action A_t, what is the probability of reaching state S_{t+1}) and reward expectations. These probabilities are then revised with accumulating evidence via **Bayesian updating** [80], which modifies the prior of the transition probability given ritual action. Crucially, these priors can also be socially learned [19], setting the agent's transition expectations even without direct personal experience [81], making the ritually scaffolded world model a basis for decision-making. In this way, repeated ritual participation not only reinforces the ritual itself but also helps perpetuate the shared world model across generations, as novices internalize both the practices and the transition probabilities and rewards associated with those practices (see Figure 2 for illustration and Box 2 for developmental stages).

World-model updating

While direct reinforcement learning can support the early acquisition of a community's world model, its later deployment cannot rely solely on continued access to social reinforcers. How is the culturally acquired world model maintained, given the unavoidable negative prediction errors arising from direct experience, especially considering that social learners are assumed to be epistemically vigilant [99]? The possible explanation lies at the intersection of model-based and model-free learning.

First, ritual outcomes are typically weakly diagnostic of ritual efficacy and have a limited effect on the socially learned prior [101]. For example, illnesses may improve on their own (natural recovery), and protective rituals often occur in uncertain, yet relatively safe situations (e.g., praying before a flight). In terms of Bayesian updating, if we assume that illness recovery occurs in 80% of cases naturally

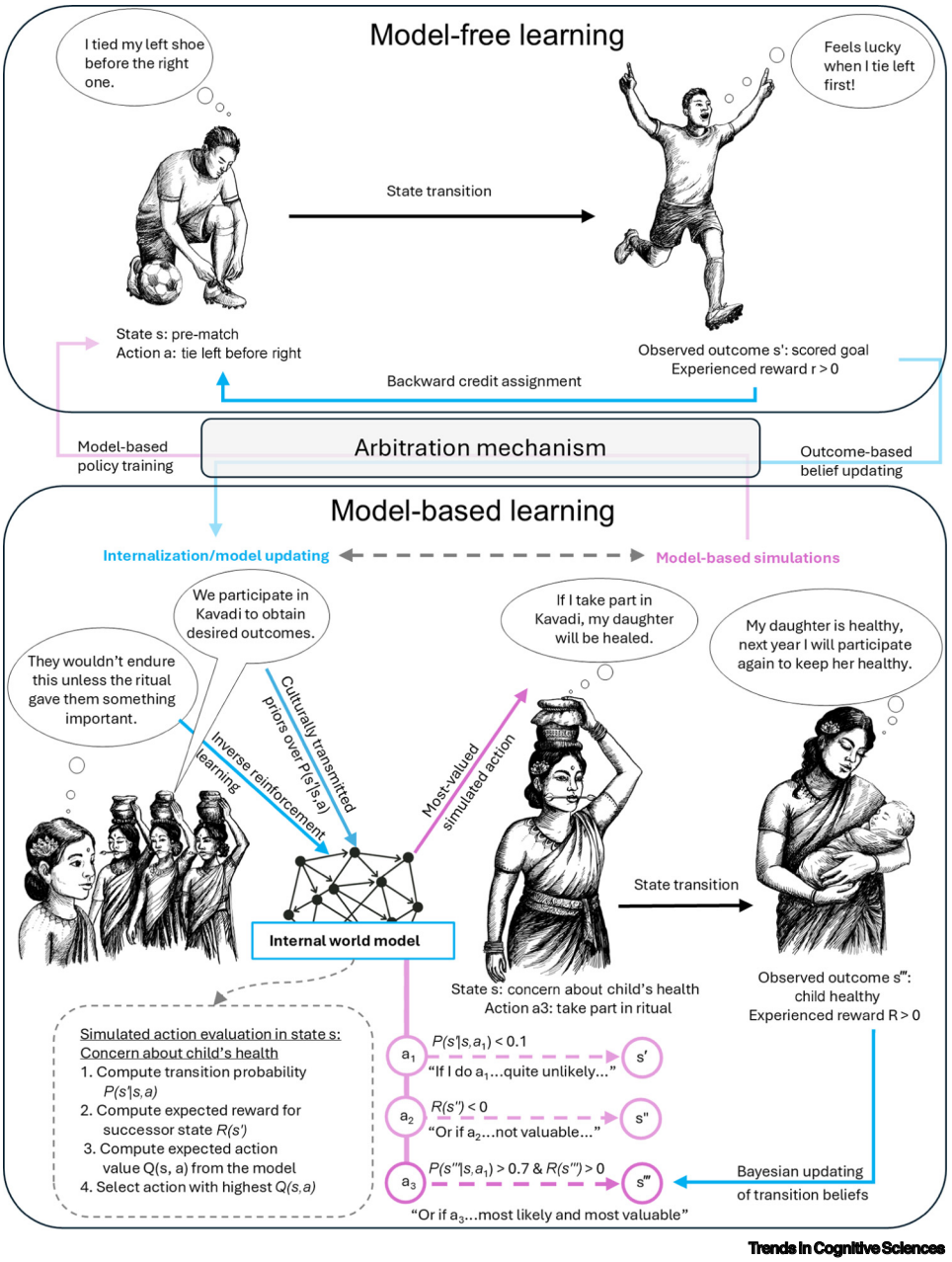

Figure 2. Model-free and model-based reinforcement learning. A soccer player experiences a positive prediction error after scoring, strengthening the cached value of the prior action via backward credit assignment. A Kavadi participant evaluates actions by simulating predicted transitions $P(s'|s,a)$ and rewards $R(s')$ using a culturally learned internal model; a positive outcome updates these beliefs through Bayesian updating. Action selection emerges through arbitration between the model-free and model-based systems, but the two systems interact bidirectionally. Model-based simulations can shape and train model-free value representations over repeated experiences, whereas model-free reinforcement signals provide outcome evidence that updates transition beliefs within the internal world model.

and in 85% of cases if rituals are efficacious, then observing recovery shifts both a skeptical and favorable prior only marginally by 0.6% upon recovery (e.g., if skeptical is 10% originally, then to 10.6%; and if favorable 80% originally, then to 80.6%).

Box 2. Developmental shifts in ritual-value updating: from model-free reinforcement to model-based world models

Learning ritual value follows the maturation of reinforcement learning systems. Developmental evidence suggests that model-free learning is the characteristic mode of learning in early childhood, while model-based learning becomes more frequently employed during middle childhood, and stable arbitration between the two systems emerges in adolescence [82,83].

Early childhood: socially reinforced model-free learning. From infancy, children are sensitive to affiliative rewards obtained by imitation, such as in synchronous movement [84]. Imitation, and especially over-imitation, are key for ritual learning because rituals are causally opaque. Indeed, young children reliably over-imitate opaque actions and treat ritualized behaviors as normative [85–87]. Imitating ritual action at this stage might be reinforced through praise, especially if coming from highly valued models, and by feeling of belonging (if majority of people around perform the ritual) [88–90]. Thus, ritual value at this stage is mostly updated via model-free reinforcement of social and affective rewards.

Middle childhood: increasing reliance on model-based learning. Middle childhood is associated with improved planning abilities and explicit reasoning, which is characteristic of model-based learning [91]. Children increasingly represent norms as abstract, group-level rules rather than household-specific conventions [92]. Ritual actions become represented as an integral part of social identity and, therefore, normatively expected. Moreover, rituals are pedagogically linked to myths, stories, and witness accounts, reinforcing socialization into the community's world model [93]. Finally, internalization is further supported by **inverse reinforcement learning**, whereby learners infer the value that the model assigns to ritual actions associated with the shared world model [94,95], as well as by pedagogical input whereby caregivers convey this value [96,97].

Adolescence and adulthood: active arbitration between model-free and model-based learning. With the maturation of model-based control, individuals can more accurately simulate future states given the range of possible actions, evaluate claims about transition probabilities, and construct auxiliary hypothesis explaining why some of the predictions might have failed in order to retain the community's world model. This developmental window may therefore be critical for consolidation or abandonment of ritual practice because alternative value systems and even world models (e.g., peer norms and expectations) become salient and might compete with the internalized childhood world model. While the predictors of consolidation and abandonment of ritual action during this period are actively discussed [98], additional insights might be gained by longitudinally tracking the reliance on model-free versus model-based learning of ritual value during middle childhood, where we would expect that the value of ritual action internalized via model-free learning might be more likely to be retained even when competing world views are present.

Moreover, rituals also occur in high-stakes environments where people may put more effort into reaching the desired outcome (e.g., people both pray and study more before a difficult exam); and in social situations, rituals are often the only proof that a new status has been acquired. Socially learned priors might also bias the weighing of evidence, with confirmatory evidence being weighted more heavily compared to counter-evidence (higher learning rates for positive rather than negative prediction errors), and failures might be attributed to auxiliary factors rather than assuming that rituals are not efficacious [19]. Thus, priors largely persist.

Second, ritual performance itself often generates immediate rewards that occur before any final outcome is known. Through backward-credit propagation (eligibility traces), model-free algorithms generate positive prediction errors that raise the expected value of the ritual action when that action presumably moves an agent closer to the desired outcome, even before the outcome is ultimately reached [23]. Together, the combination of resistant transition beliefs and positive model-free reinforcement helps explain how ritual practices stemming from a culturally shared world-model remain stable across generations, even when their causal efficacy cannot be empirically verified.

As a caveat to this interpretation, individuals, of course, do revise their beliefs and sometimes abandon ritual participation [101]. This is especially likely when the socially learned priors are weak (e.g., due to weak socialization into the value of ritual or inconsistent ritual performance by cultural models [94]) and the expected value of maintaining a given world model declines.

Under such conditions, some ritual behavior may persist, but primarily through affect-driven reinforcement processes that sustain participation via immediate emotional and social rewards.

Religious rituals merge the supernatural and the normative

In many cultural systems, socially acquired world models include powerful supernatural agents who are believed to influence human well-being in both this life and the afterlife [102,103]. While we have so far discussed the general aspects of rituals, ritual performance is typically associated with the veneration of deities. In line with the proposed reinforcement learning interpretation, actions such as prayer, sacrifice, or participation in collective worship are evaluated prospectively using model-based simulations of expected consequences, both immediate (e.g., divine favor) and deferred (e.g., salvation [11]). Thus, a petitionary prayer before a long drive may be computed as a relatively cheap action that might substantially reduce the danger of an accident, assuming the agent believes that divine intervention is a real causal pathway.

Crucially, many religious systems condition supernatural benefits, such as protection, healing, or success, on an individual's adherence to community norms, because supernatural agents are often represented as mandating moral norms that the group upholds [103,104]. In such contexts, ritual participation and normative behavior are encoded within a shared world model in which supernatural and social consequences are interdependent. For individuals who have internalized this model, the expected value of ritual participation therefore integrates both model-based predictions about supernaturally mediated outcomes (e.g., healing [41]) and the socially mediated responses of other community members (e.g., increased trust or willingness to help [5,16,17]; see Box 3 for illustration).

For individuals who do not share the community's world model, the expected value of ritual participation is low because the transition from ritual action to supernaturally mediated outcomes has a negligible probability and, therefore, is unlikely to lead to a reward exceeding the cost of the performance [11]. Although such individuals can anticipate the social responses associated with participation, their model-based evaluation lacks the supernatural outcomes that believers encode. Consequently, the total expected value of high-cost ritual actions remains too low and is unlikely to be selected, which might help explain why participation in costly rituals functions as a reliable signal of adherence to the communal normative and belief system (see [40] for an empirically inspired computational treatment of how efficacy beliefs are integrated into the expected value of ritual participation).

Box 3. Thaipusam Kavadi in Mauritius: personal vows and public signals

Thaipusam Kavadi is an example of an extreme ritual combining pain, effort, and endurance (Figure I). Celebrated by Tamil communities, the ritual honors the god Murugan, who is believed to grant or fulfill vows made by kavadi bearers.

Participants undertake a period of purification that includes abstaining from meat, sex, and intoxicants before performing an arduous pilgrimage to a temple, often barefoot or walking in the shoes of nails and under the tropical sun. Many pierce their skin, cheeks, or tongue with sharp needles and skewers as acts of devotion, carry elaborately decorated wooden or metal structures on their shoulders (called kavadi, i.e., 'burden'), or drag temple chariots with hooks attached to their skin. See the accompanying photo on the left from Thaipusam Kavadi performer in Mauritius.

Participants frequently describe their motivation as part of a covenant with Murugan: seeking divine favor for healing, protection, or success in business [9]. Yet, empirical studies have shown that participation in the Kavadi predicts larger monetary donations to the temple compared to prayer [106], and observers consistently rate Kavadi participants as more devout, trustworthy, and norm-abiding than nonparticipants [11]. Parents even report a preference for Kavadi devotees as potential sons-in-law [107]. These findings illustrate that ritual participation might be motivated by both reaching personally desired pragmatic outcomes and by signaling commitment to a community's norms and beliefs. Thus, Thaipusam Kavadi exemplifies how these value computations become intertwined and even lead to extreme performances.

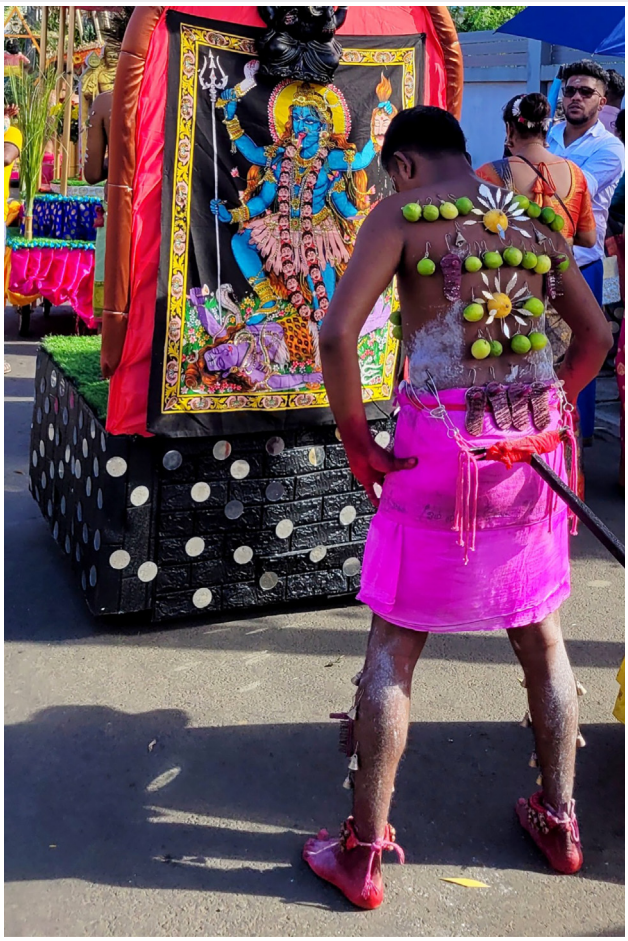

Figure I. Illustration of costly ritual participation.

Importantly, while we illustrated how religious rituals might differentiate between committed members and free-riders using the model-based learning architecture, repeated ritual performance can further strengthen this effect by transitioning to the model-free mode. When ritual contexts become familiar, decision-making is more likely to rely on well-reinforced, model-free heuristics [108] that require minimal cognitive effort yet have a high probability of yielding culturally valued outcomes [109]. Indeed, a recent study showed that cooperators rapidly deploy costly signals of commitment, even under experimentally imposed time pressure that prevents model-based evaluation and reduces the opportunity to compute signaling payoffs [110]. Frequent performance of religious rituals may, therefore, rely heavily on model-free decision-making, which draws on action policies that were originally shaped by model-based representations of supernatural and social contingencies but, once learned, can be executed rapidly and with minimal cognitive effort and effectively increase the separation between committed and uncommitted individuals.

Empirical predictions from the proposed model

Insights from this review open promising avenues for future empirical research (see also Outstanding questions) and offer several testable predictions regarding the distinction between

model-free and model-based learning. For example, when differentiating between novices and dedicated members, novices should rely primarily on model-free learning, reinforced through social and affective rewards, and such engagement is expected to be low-cost. When substantial costs are required (e.g., painful or scarring initiation rituals), the value of participation for novices is more likely to be computed through model-based engagement [72], and these evaluations may likely lead to disengagement (unless group membership is essential for survival). These predictions are consistent with ethnographic observations of religious conversion processes [111], but controlled laboratory experiments are scarce.

Conversely, we would expect that for committed members, even high-cost rituals may be evaluated as having net-positive value, thereby distinguishing dedicated from uncommitted individuals [17,51]. Repeated performance may even shift decisions on whether to participate in such rituals into model-free control, such that their value is no longer computed through model-based simulation each time but is instead retrieved automatically from memory for dedicated members. Such individuals would also be predicted to be less sensitive to disconfirmatory evidence regarding ritual efficacy (e.g., baseball players often perform rituals they do not believe have a causal impact [112]).

The model-free/model-based updating of ritual value should also be moderated by personality characteristics. For instance, the need for cognitive closure should predict greater model-free dominance [28] with weaker learning rates and greater belief–behavior decoupling (emphasizing ritual orthopraxy). The same might apply to trait anxiety [113], where we would expect reliance dominantly on the affective rewards provided by ritual. Need for cognition [114], on the other hand, should predict stronger model-based control and tighter belief–behavior coupling.

Looking at cross-cultural variation, in tight cultural contexts (as compared with loose cultures), where norms are strong and social monitoring is high [115], ritual value should be anchored disproportionately in social rewards, producing a decoupling between private efficacy beliefs (which might be low) and social rewards (which are high). Even when private efficacy beliefs erode, the collective ritual should still be performed. On the other hand, highly orthodox religious systems (restricting the range of acceptable beliefs as opposed to more syncretic religious systems) would be expected to tighten the prior about ritual efficacy beliefs, relying on auxiliary hypotheses to explain disconfirmatory evidence and reducing learning rates following negative prediction errors. In both tight cultures and religious orthodoxy, we would also expect eligibility traces to decay more slowly (higher λ), allowing credit assignment to the whole ritual section even when outcomes occur later. In looser cultures, traces would decay more rapidly (lower λ), concentrating learning on actions immediately preceding outcomes and allowing for ritual innovation at a faster pace.

Concluding remarks

Ritual behavior can be formalized as an integration over multiple value sources operating at distinct computational levels. At the model-free level, ritual actions acquire value through direct reinforcement learning via reward-prediction errors related to specific outcomes, such as reductions in anxiety or heightened social cohesion. Yet, rituals are most powerful when they establish a shared model of the world.

At the model-based level, ritual value is computed through the evaluation of possible actions within culturally structured generative models. These community-specific models link ritual performance to pragmatic rewards (e.g., protection during travel and salvation in the afterlife) as well as social rewards (e.g., cooperation and status). The resulting value function thus

Outstanding questions

Do cultural systems vary in their emphasis on model-free versus model-based reinforcement of ritual value? What are the predictors of such emphasis?

Do cultural systems other than religions merge the pragmatic and social functions of rituals to sustain cohesive and cooperative communities? If so, are those communities as successful as religious groups?

What are the developmental stages through which individuals acquire their community's generative model of the world, and how does ritual participation at each stage reinforce the internalization of these models? Are there critical or sensitive periods during which ritual engagement is particularly effective in stabilizing culturally specific causal and moral expectations?

In which situations do individuals rely more on model-free reinforcement (habitual repetition and emotional regulation) versus model-based inference (belief-driven reasoning about outcomes) in sustaining ritual participation?

How might computational models of ritual help explain the persistence of conspiracy beliefs in modern societies, where shared generative models are reinforced symbolically rather than through collective ritual performance? Are adherents of a particular conspiracy capable of effective collective action without ritualized signaling of cooperative intentions?

What cognitive, social, and environmental factors predict the decline of ritual value and eventual abandonment? Do reductions in perceived supernatural efficacy or in social-reputational benefits differentially drive this decay, and how can such processes be captured computationally?

integrates immediate, experience-based reinforcement with model-based rewards grounded in the internalized community's world model.

This framework integrates several major accounts of ritual persistence. At the proximate level, instrumental and uncertainty-management theories suggest that ritual helps to regain control over pragmatic goals and regulate anxiety [46,112,116,117], whereas social cohesion and signaling accounts stress the important role of rituals in facilitating a group's cooperative output [10,51,59,106]. The presented synthetic framework specifies how these distinct value channels can support ritual persistence in parallel and, importantly, become interlocked: pragmatic or affective reinforcement can stabilize repeated performance, while social reinforcement maintains shared expectations that make ritual participation valuable via cooperative benefits, while also supporting belief in ritual efficacy [40]. At the ultimate level, pragmatic ritualization can be treated as a by-product of humans' tendency to intervene in the real world under uncertainty [18–21], whereas the social and cooperative functions emphasized by cohesion and signaling accounts can contribute to the long-run stability of ritual practices [13,16,17].

There are, of course, areas where the synthetic framework would be less informative. For instance, understanding specific ritual forms might be limited since they are shaped by stochasticity and path dependence [118]. Similarly, the framework does not explain practices whose primary function is aesthetic or entertainment (e.g., ceremonies and festivals) [3].

Finally, despite highlighting the social function of rituals, we do not mean to imply that rituals are inherently a force for good. While they can promote intragroup cohesion, such cohesion often comes at the cost of intensified intergroup division and outgroup hostility [119,120]; although it should be noted that rituals can also facilitate peacemaking and restore intergroup relations [121]. Ultimately, rituals are a culturally evolved social technology that amplifies cooperation, commitment, and shared world models—that is, mechanisms that can be harnessed for either constructive or destructive ends. In this regard, a key challenge for future research is to determine how the reinforcement and transmission mechanisms reviewed here operate in digital environments, and whether the absence of physical ritual performance might alter the architecture of credible cultural transmission, potentially contributing to the spread of misinformation and political polarization [122].

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Declaration of interests

The authors declare no competing interests.

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